THE IMPACT OF MODULAR SHIP DESIGN OF THE LIFE CYCLE OF A NAVAL VESSEL

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B.S., United States Coast Guard Academy
(1970)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
OCEAN ENGINEER
AND THE DEGREE OF
MASTER OF SCIENCE

in

SHIPPING AND SHIPBUILDING MANAGEMENT

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Submitted to the Department of Ocean Engineering on 7 May 1976 in partial fulfillment of the requirements for the degree of Ocean Engineer and the degree of Master of Science in Shipping and Shipbuilding Management.

ABSTRACT

The need for increased modularity in Naval ship design is approached by first of all considering and examining the overall design in two different areas: the required effort and trends in the design process and the evolution of the design process itself.

The growth in design effort in terms of participation and man hours and the trends in ship design such as increasing size, powering, software, etc. are discussed in order to point out the increasing complexity of Naval ships. The impacts of these trends on the actual design process are then analyzed. This is accomplished by briefly reviewing and comparing the conventional, CF/CD and present design process and discussing their advantages and disadvantages. Finally, the present design approach is analyzed in order to point out some of the drawbacks and impacts of the "Design to Cost" philosophy.

The ship is next looked upon as an investment and procedures are analyzed to increase the Navy's return on this investment over the ship's life cycle. Some of the major problems facing the Navy today in ship acquisition are discussed and in all cases the incorporation of modularity appears to be the best solution to these problems and create the best ROI over the life cycle.

Finally the modularity state of the art is covered and a methodology presented to aid the designer, and operator in selecting a level of modularity that best meets his needs under different design philosophies.

Thesis Supervisor: Ernst Frankel
Title: Professor of Ocean Engineering

ACKNOWLEDGMENTS

I would like to thank my thesis advisor, Professor Ernst Frankel, for his enthusiasm, support and advice during the preparation of this thesis.

I would also like to acknowledge the love and support of my fiancee, Jill Wilkinson, that she has given me in the preparation and completion of this thesis and over the past two years.

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1.1 Complexity of Naval Ship Design

The unique characteristic of a naval ship design process is determined by three items; 1) technical complexity, 2) long life, 3) high unit cost and small numbers. The design of an extremely versatile, powerful weapons system is a vastly complex process, and perhaps could be considered an engineering marvel. The number of subsystems and components comprising the ship system and the technical complexity and precision involved in the integration of the subsystems into a homogeneous system so that it performs its designed missions effectively for a life time of 25 years or longer is quite immense.

Few engineering tasks require more man hours and have a higher degree of technical complexity and design effort than a naval warship. For instance studies recently conducted at MIT showed that a DLG required approximately six times the design effort as that of a supertanker, ten times that of a land based utility station power plant, and about three times that of a major airport. These figures were basically arrived at by using an arbitrary weighing system on the number of man hours, decision input, trade off studies, and technical expertise required to produce the design. Basically a warship is so much more sophisticated because it must be an effective multi-mission, mobile weapon

system operating in all oceans of the world. It must keep pace with the enemy threat and the rate of change of technology. It must have long endurance and be able to make repairs underway without the assistance of outside activities. Finally it requires a large range of skills to operate and probably has the highest life cycle cost of any other piece of engineering.

1.2 Trends of Naval Ship Design

Naval ship design has followed several definite trends over the past half century and has seen obvious increases in the amount of effort required for the design, the complexity of the hardware, and the use of software in the ship system.

1.2.1 Design Effort

First of all to produce a warship a closely knit design team is required comprising wide ranging engineering talent, experts in the operational area and the managers to efficiently and effectively coordinate the above two groups. It is this group of people upon which the performance of modern naval ships depends.

The size of the design community and the number of man hours spent in the design effort has escalated quite sharply since 1940. Figure 1 shows the number of man days required to complete a contract design for seven frigates plotted against the date of design completion

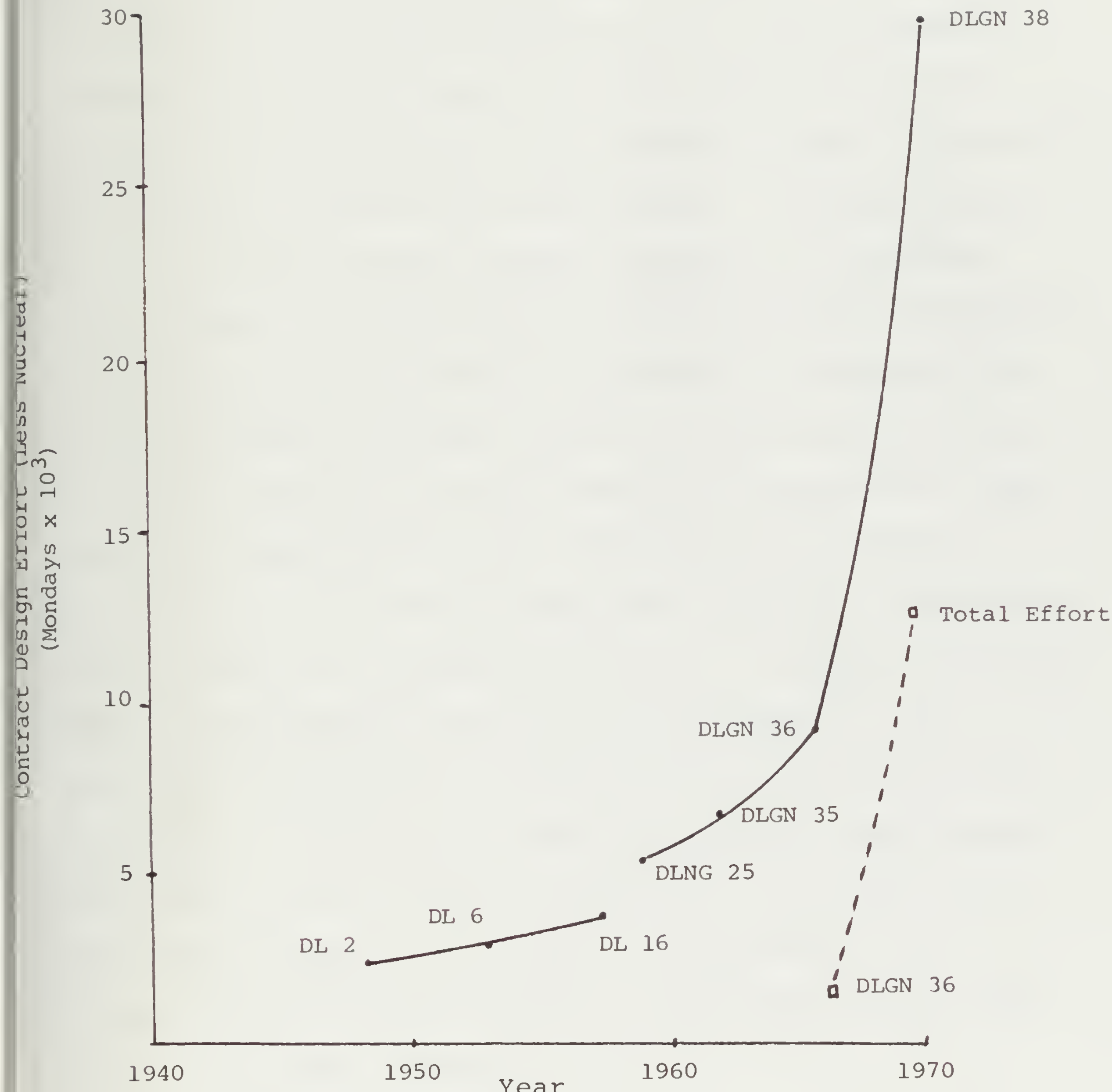


FIGURE 1 The Increased Effort Required to Produce a Ship Design (8)

What is evident is the newer designs requiring increased design effort and the strikingly sharp escalation in design effort for the DLGN 38. However, several points should be made to clarify the graph. First of all the man day effort is for contract design only or the preliminary contract and detailed design in todays terminology, and primarily involves the hull and machinery design. In addition the contractor electronics design effort is excluded along with the weapons system, although weapon/hull interface was addressed. Also the three nuclear designs do not include the propulsion design effort. Although this does not give an absolute magnitude type picture, it does point out that the effort required to produce naval ship designs has been steadily increasing with time. Obviously to include all facets of the design would merely mean scaling up the design effort access by an appropriate factor. The amount of design effort is considered a function of two items, 1) the efficiency of the design process and 2) the complexity of the design. Obviously an inefficient design team requires more effort than one that is organized. The design team's efficiency depends on the number of participants, the frequency at which the community is exercised and how they utilize the latest techniques.

1.2.2 Technical Complexity

The second trend in naval ships is in the area of technical complexity which is probably the reason for the escalation in design effort. The more complex a system is the more design effort required. In any event what this means is that the hardware such as payload/weapons systems, propulsion, auxiliary and hull subsystems are much more sophisticated. An indication of this fact would be the increasing vessel displacements for a given type ship over the past half century, (Figure 2). The increased displacement results largely from the increased weapons, payload, and manning requirements which in turn impacts the propulsion and auxilliary equipment sub-system, Figures 3,4,5.

There are several points to be brought out in Figure 2. First of all the new DD 963 presently under construction approachs the same size as WWII light cruisers. The present day single screw "DE" is larger than the twin screw WWI destroyers, and todays nuclear powered frigates should be considered cruisers. The other illustrations merely support the fact of increasing ship displacement with time.

The increased installed horsepower and complexity is a result of the increased ship displacement. The electrical and air conditioning requirements are increased due to increased manning, and electronics subsystems, Figure 6. Obviously more sensor and communications

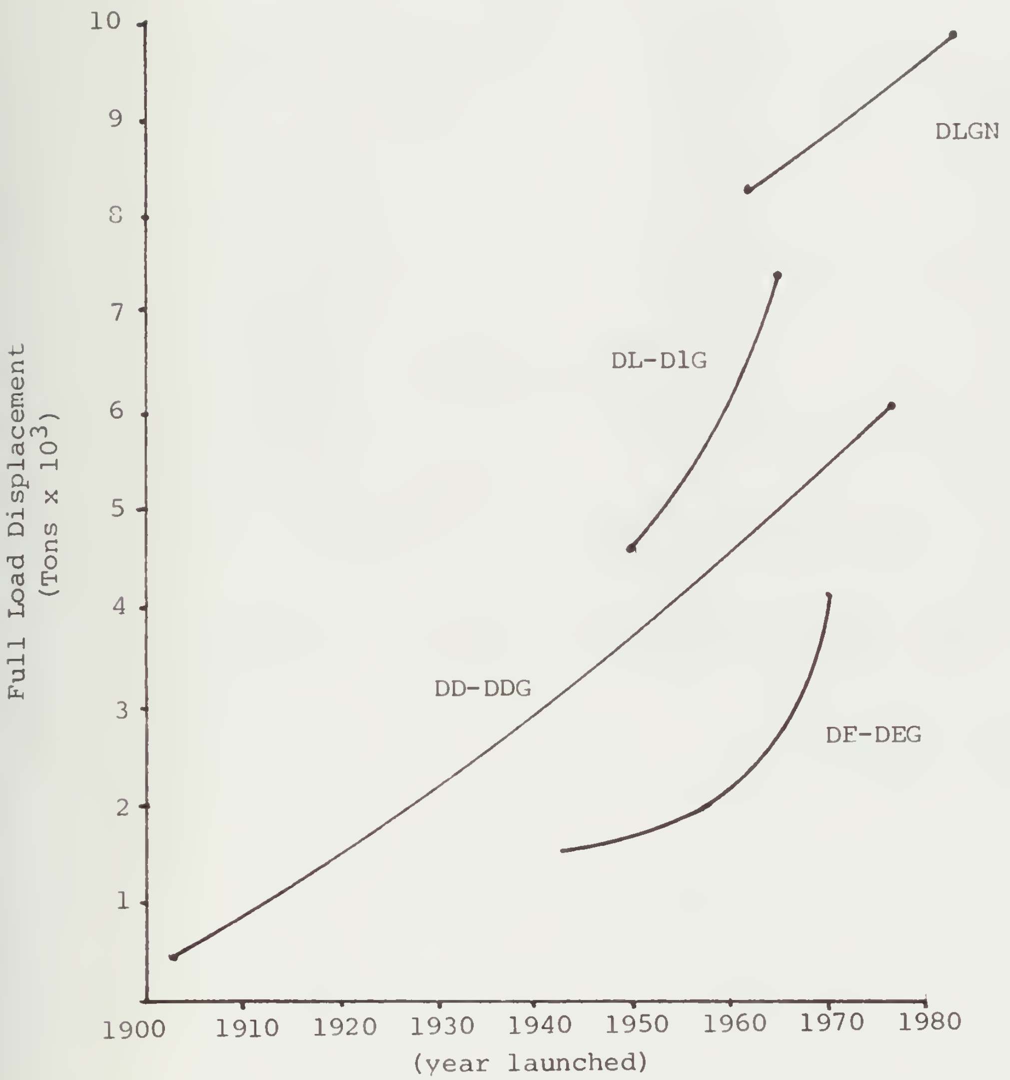


FIGURE 2 Growth in Ship Size as Indicator for Increased Ship Hardware Complexity (8)

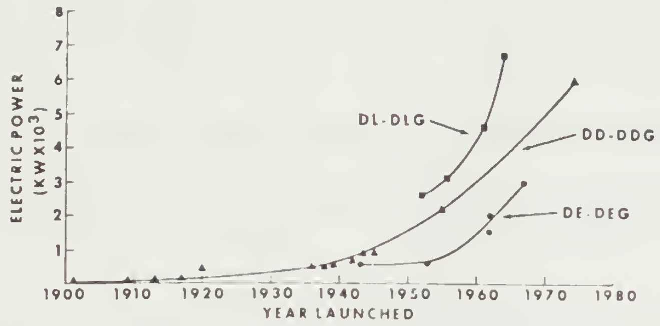


FIGURE 3 Growth of Electrical Power (8)

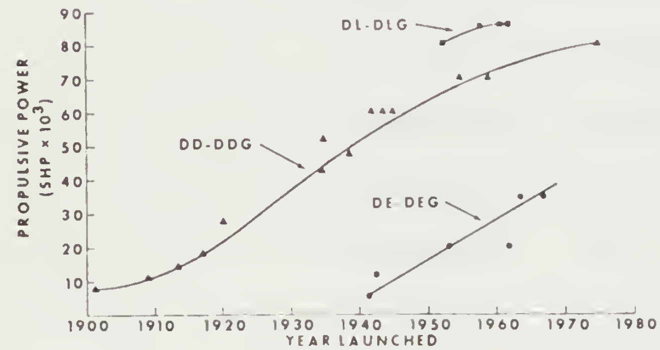


FIGURE 4 Growth of Propulsive Power (8)

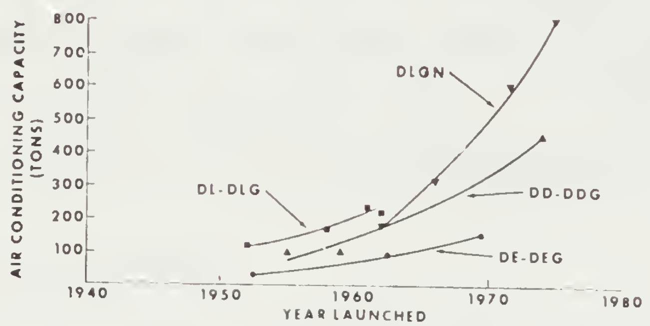


FIGURE 5 Growth in Air Conditioning Capacity (8)

require greater power and cooling capacities. By nearly every measure it is evident that not only are today's ships more powerful but they also contain an ever increasing number of subsystems and components which equals greater complexity.

The reason for the increased complexity is easily traced to the increased performance requirements requested by the operators. Todays ships are required to have increased endurance, availability, automation, habitability, shock resistance, quicker response to enemy threat and reduced noise emission. In the area of response time WWII destroyers were designed for 25 minutes, whereas todays vessels can meet enemy threats in one to two minutes. Our vessel reaction time must keep pace with that of the enemies, therefore, the enemies increased capabilities has been a major driving force on our own ship design.

With the shift to the all volunteer service, ship board habitability has to be attractive and comfortable. As a result today's ships have twice the living area per man as compared to WWII designs, Figure 7. Obviously there has been a shift in design philosophy here.

1.2.3 Miscellaneous Trends

Finally the trend in software associated with the ship design process has seen a steady increase since WWII days. This increase is a direct result of the vast amount

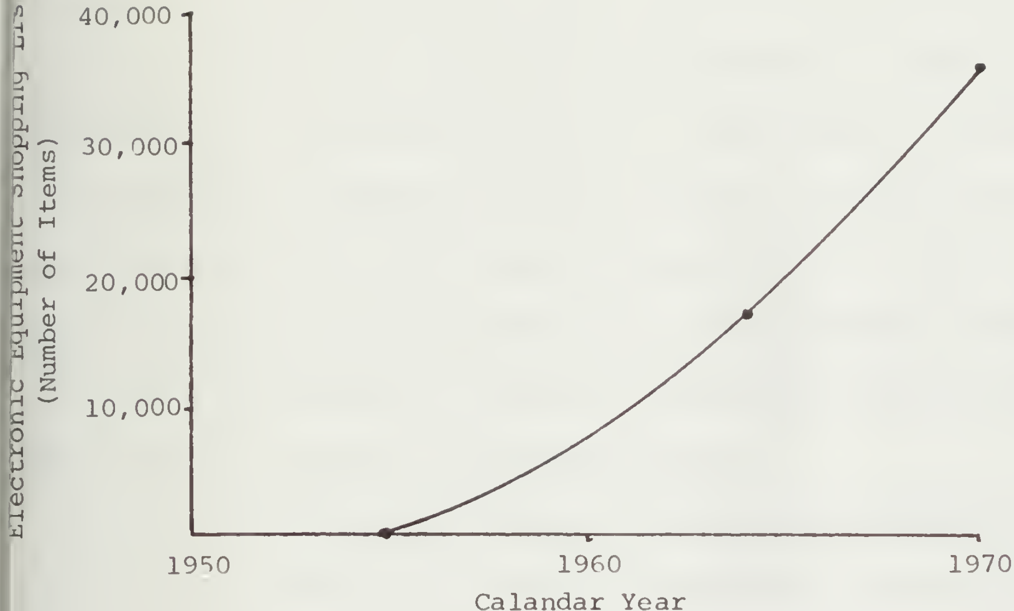


FIGURE 6 Growth in Size of Electronics Shopping List as an Indicator of Increased Ship Hardware Complexity

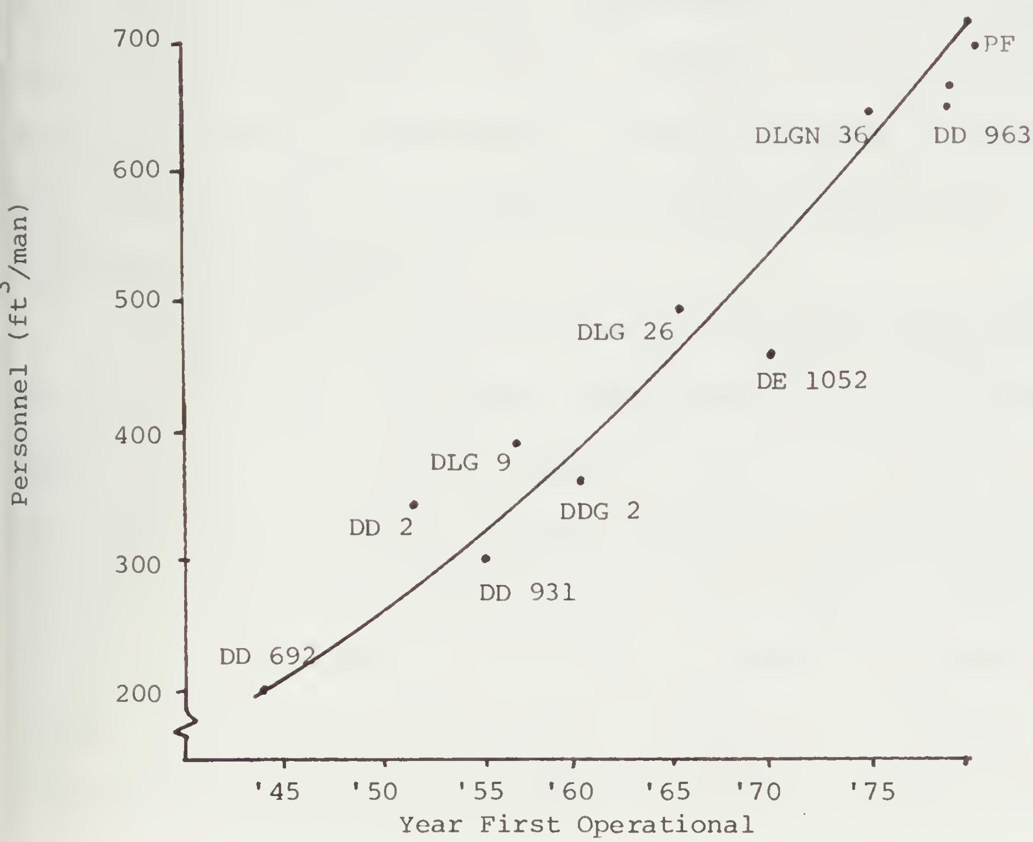


FIGURE 7 Habitability Trend [26]

of documentation required in performing all the trade off studies and because of the more complicated design of the hardware. Figure 8 depicts the increased number of drawings in keeping pace with our more complex designs. In addition the emphasis on reliability, maintainability and availability, IIS, human engineering and safety previously taken for granted has significantly increased in todays priorities of design philosophy thus adding to the software package and documentation.

In recent years greater industry participation has occurred in the design effort in contrast to the previous "in house" effort. Also the acquisition process involves firm fixed price contracts. Therefore design results have to be transmitted formally between industry and the buyer and the various aspects of the contract require more detail even to the smallest items in order to eliminate any ambiguity.

Documentation has also been increased because of the change in project management and because of the increase design effort in terms of people involved. Trade off and cost effectiveness studies are being examined at higher levels of management before major decisions are being made.

Finally computer software is requiring greater effort in preparing the computer program performance specifications during the contract design period. Many

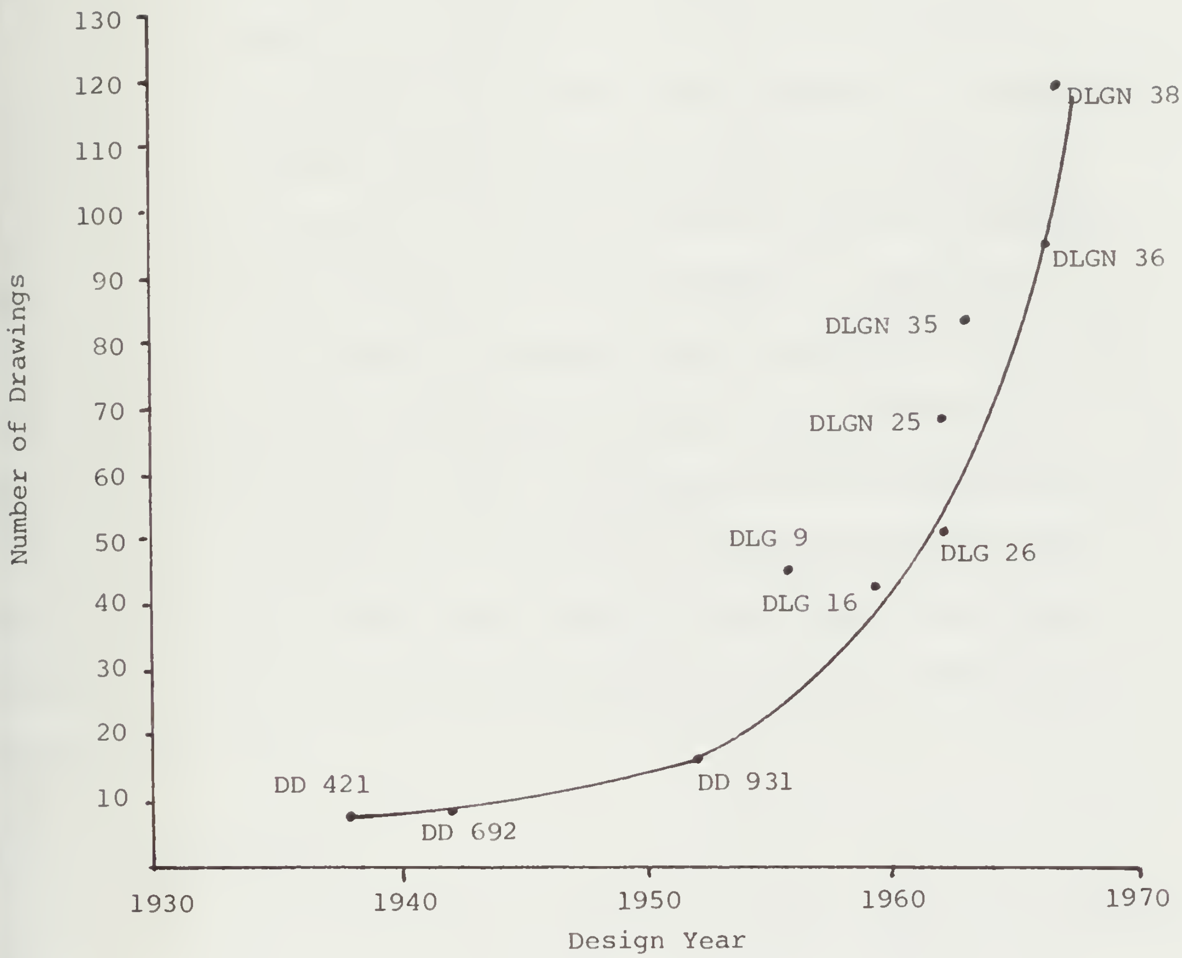


FIGURE 8 Growth in Number of Contract/Contract Guidance Drawings as an Indicator of Increased Software Complexity (8)

portions of the combat system components are employing digital computers which of course must be programmed and integrated into the entire system. This digitizing of the combat system amplifies the documentation magnitude.

The graphs that follow are provided to further demonstrate that the design effort and complexity is forever increasing. However several points should be brought out. Destroyer size has been increasing over the past two decades until the "design to cost" PF and DD ABGIS. Although size has been increasing installed shaft horsepower has not kept pace, therefore a decreasing speed trend results for the DD-DLG-DLGN class. This trend may also be explained by the gradual increase of importance of acquisition cost habitability, and life cycle cost in the design and less importance being placed on performance without regard to acquisition cost.

1.3 Introduction

These trends in ship design have been pretty much the result of a necessity rather than a desire. Because of the increase enemy threat and increased requirements of ship design it is necessary to incorporate a greater effort, more people, more documentation, more computer software and more drawings. Unfortunately, all these increases make a more expensive ship and a longer design period.

Today especially with defense budget cutbacks, out ragious inflation and very fast pace of technology it appears that the ship design trend is leading in the wrong direction. The truth is that these are real life situations facing eh Navy. The combined effect of a long design process and high rate of obsolesence makes for a very short useful life for new ships before a Modernization and Conversion (M&C) is needed. The problem is further compounded because the Navy loses alot of ship availability when ships undergo early M&C. In addition the shortage of sea going personnel and high manning costs faces the designer to go to more automated devices. The final result is that the Navy needs to design and build more ships with greater availability with less money and with essential manning in mind.

In the following chapters the history of the design process is outlined and the philosophies driving these processes are analyzed. Emphasis is placed on the present design approach which follows the Design to Cost philosophy and then comments are made on its drawbacks. The final two chapters suggests a design approach to alleviate some of the problems mentioned above and eliminate the drawbacks of DTC.

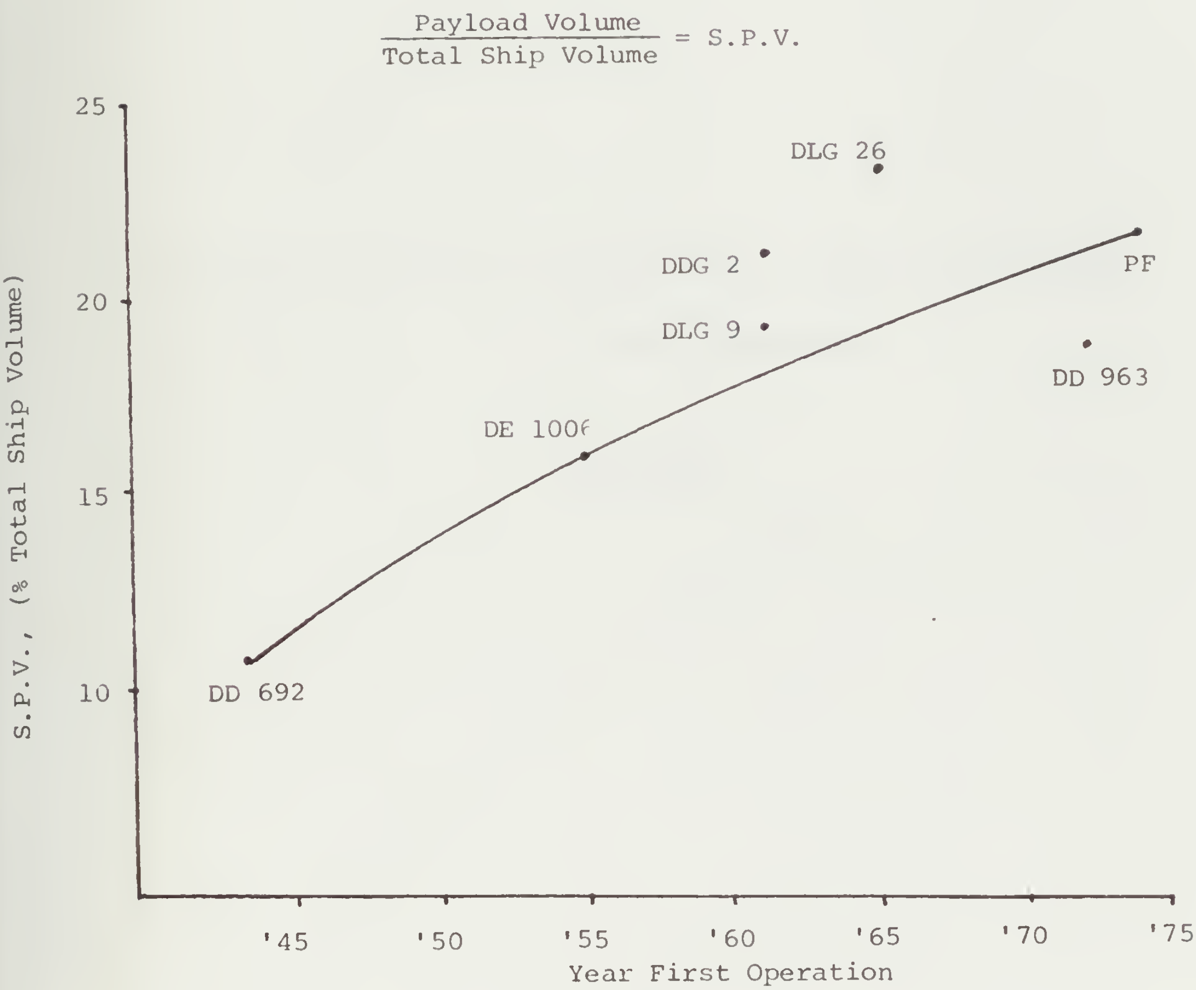


FIGURE 9 Specific Payload Volume Trend (26)

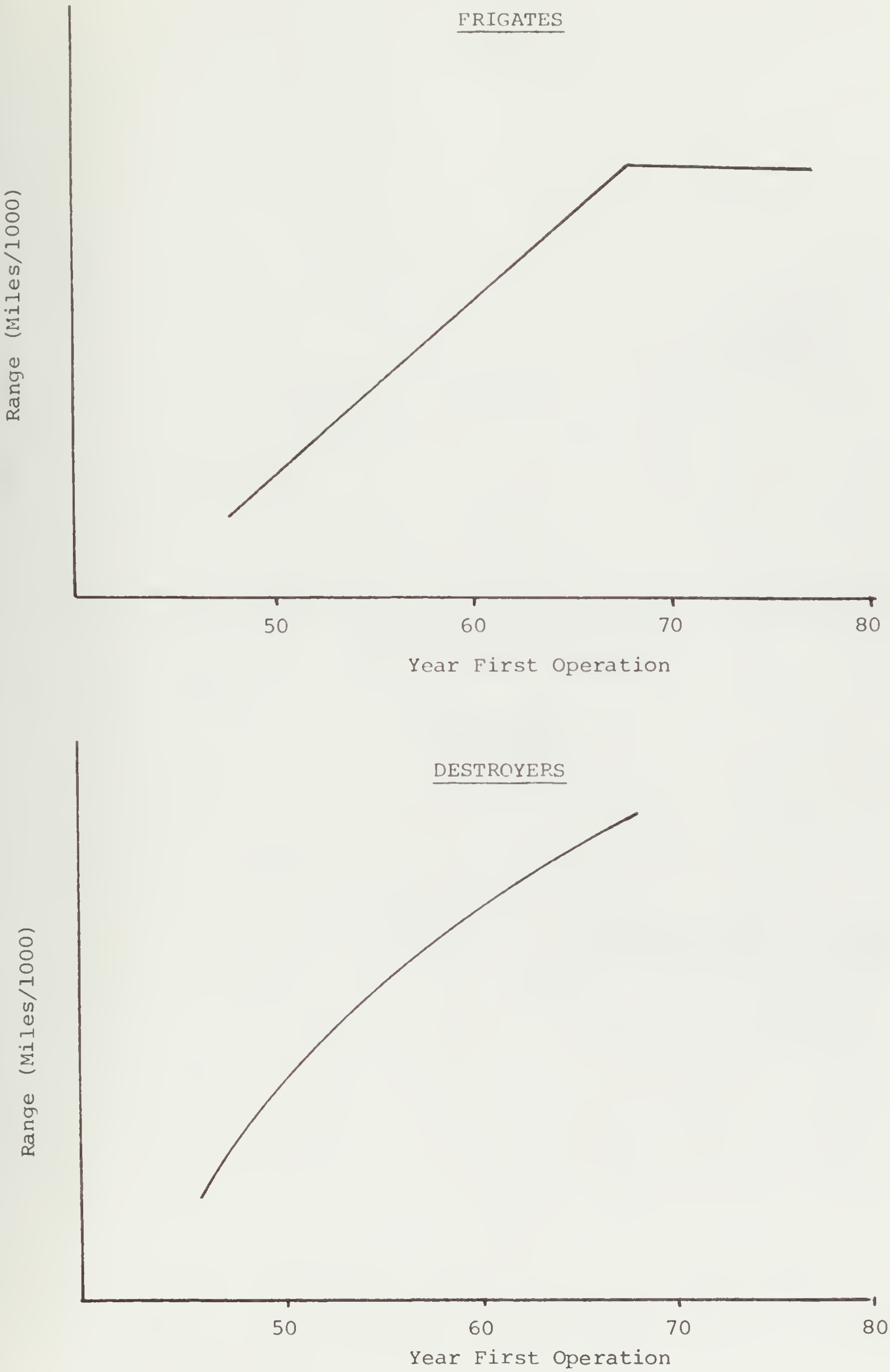
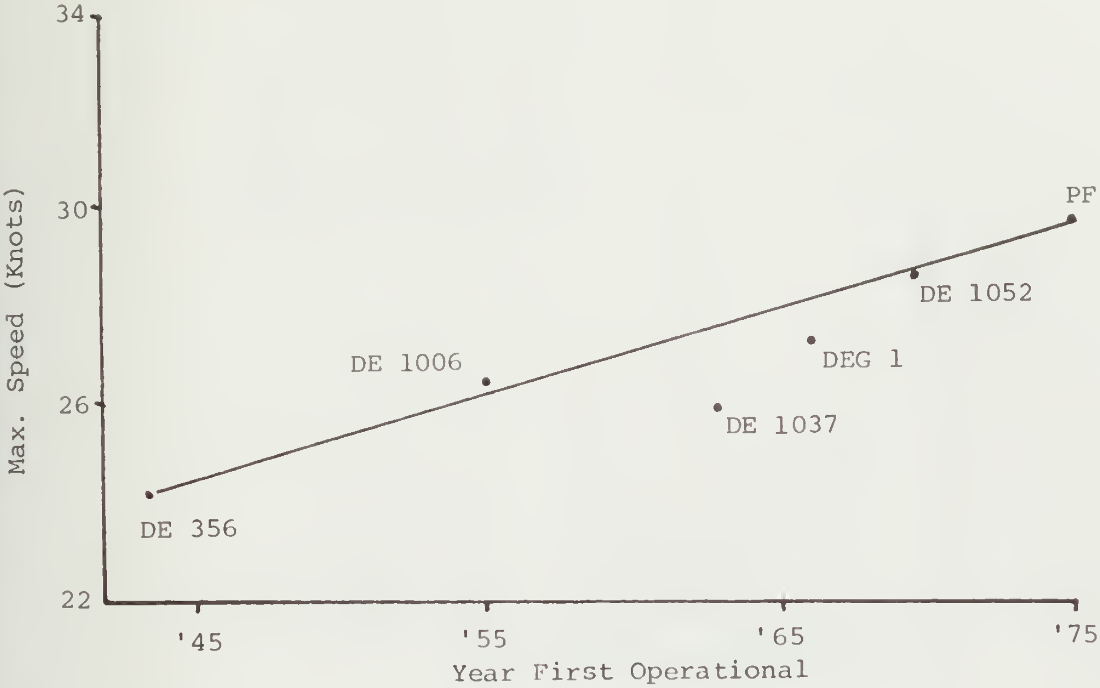


FIGURE 10 Endurance Trend (26)

DE-DEG



DD-DLG-DLGN

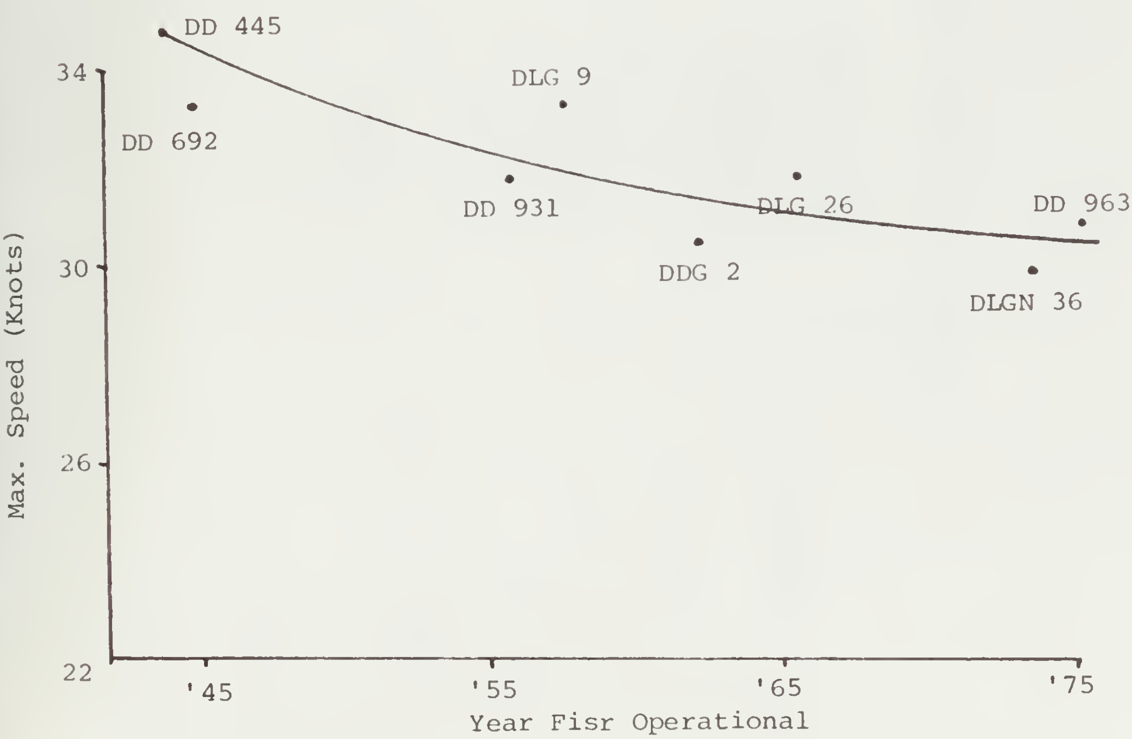


FIGURE 11 Destroyer Speed Trend[26]

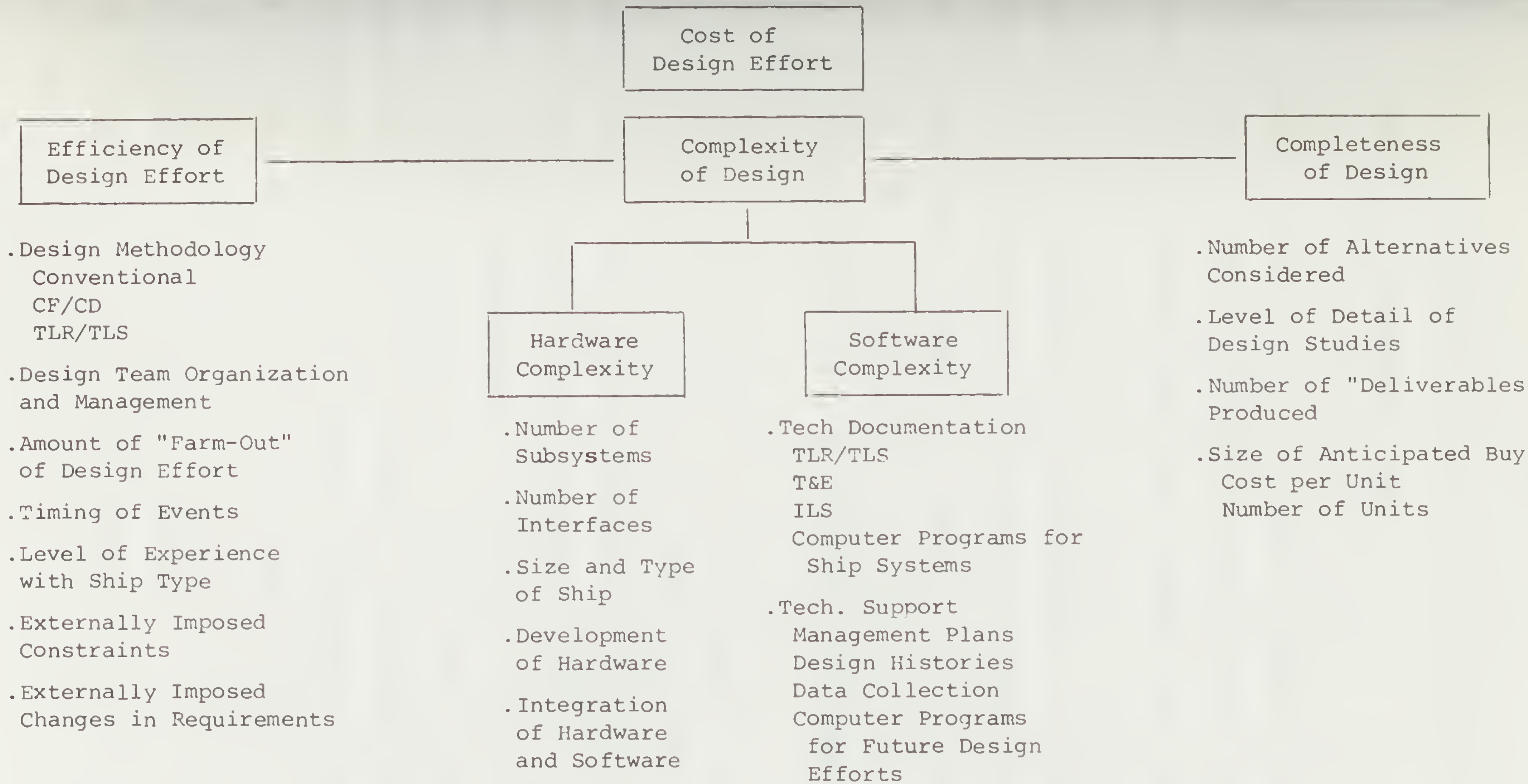


FIGURE 12 Categorical Factors Affecting Ship Design Costs [26]

2. Ship Acquisition Policies and Practices

.1 Outline of Basic Ship Design

The naval warship design process over the past /2 century has evolved into a highly sophisticated process consisting of a wide spectrum of talent in the design community, thousands of man days and over ten years until the first ship's keel is laid. However during this period there have been some significant changes in the Navy's approach, organization and philosophy towards the laborious design process. A review of past and present practices will be presented in order to show the magnitude of the effort and to point out the Navy's changing attitude.

First of all a ship's life cycle may be broken down into well defined steps with the first being the Conceptual Design Phase. This phase commences with the feasibility study which, with the operators basic statement of need, makes a wide ranging search of concepts. That is it investigates all alternatives. Also in this phase the design constraints and performance requirements are established based on the owner's statement of need. The design requirements consist of a specification of the operational and technical performance that the concept must meet. In other words -- what must it be able to do and how should it do it? The design constraints are parameters which must be met or not exceeded. Emphasis

the conceptual design phase and a duration of 10-12 months.

The decision to continue to the next phase of the design is made in-house and is based on the answers of some fundamental questions: 1) are the performance requirements firm? 2) has the size and cost been established? 3) do we have the best concept? 4) are the technical risks manageable?

If the design community feels confident about the answers to the above and after all supporting documentation has been completed and the decision to go on is made, the preliminary design phase is commenced.

The preliminary design phase mainly concerns itself with the identification of all the technical interfaces associated with the ship's sub-systems. All trade of decisions are made on the component level which is based on a design criteria established at the beginning of this phase. In addition a complete engineering description of an integrated ship system must be achieved such that the basic ship size and definition will not change during contract design. Also a functional definition of integrated sub-systems selected for optimization of total ship performance and cost must be achieved. As mentioned previously a final design criteria is selected for the whole ship entity characteristics.

The whole effort in this phase begins with one concept and completes the engineering decision of the design which is under taken by 80-90 engineers in-house and in the technical community with a duration of 10-12 months.

Once again a functional baseline is drawn up which includes documented trade-offs and the top level specifications. A decision is again thrown up at this point on whether to commit more money and push the design on into the contract design phase or drop the project as it stand. This decision is, of course, made by the secretary of defense.

The contract design is the last big push to the finished product. Once this stage has been entered then chances are good that the project will be carried out to the construction phase. This effort consists of approximately 100-300 engineers and 12 months duration in which the fine details of the design are worked out so that industry can make a class A estimate. Finally a contract is awarded and land based test sites for various sub systems are set up.

Once a builder has been chosen the design effort essentially shifts from in house to out of house so that working fabrication and construction drawings can be worked up. This is primarily done by the lead ship builder.

With this design process in mind the phases of a ship's life cycle is summarized below:

1. Conceptual Design Phase	In House Work 3 Yrs.	Engineering Development	Ship Acquisition 5-12 Years
a. Feasibility Studies			
b. Concept Design			
2. System Design			
a. Preliminary Design			
b. Contract Design			
3. Production Phase			
a. Detailed Design			
b. Actual Construction			
4. Delivery		Operational 25-30 Years	
a. Test and Evaluation			
b. Logisties Support			
i. i.e. Train Crew			
ii. Space Parts & Tools			
iii. Technical Manuals and Publications			
5. Operational Phase			
6. Maintenance and Modernization			
7. Retiring			

2.2 Conventional Approach

The design process however has changed significantly in the past 40 years and in fact the above sketch of a ship design process is representative more of that of the pre 1960 period which is known as the conventional acquisition process. The various phases and the decisions and design effort have changed little since then however the basic characteristics such as who actually does the work (i.e. in house or out of house) and the cost consciousness has changed greatly.

For instance the conventional process as previously outlined consisted of the concept, preliminary, contract and detail design. The majority of the effort was done within the Navy (in house) on a non-regorous level with little documentation and design control being kept. Costs were of secondary importance and in fact relatively unconstrained whereas the performance was optimized. In addition, multiple ship yards were involved in the contract. As a result of the non regorous approach and performance optimized philosophy the whole process was pretty much characterized by cost overruns, schedule overruns, and lacking performance, (Figure 13).

2.3 CF/CD

Obviously the conventional design approach was inadequate to economically and efficiently fulfill the

needs of the Navy in designing ships and a new approach was needed. In the mid to late 60's a major shift in participation occurred from essentially in house to out of house. The rational behind this move was that significant costs savings could be realized in the design process if advantage were taken of the profit motive incentive of industry and have strictly an "out of house" design. The profit motivation associated with a multi-ship contract is that of improving labor efficiency. Previously in the conventional process not enough time and only about 1-2% of the acquisition cost was spent in the design phase. In addition there was a shift in the philosophy of the balance between cost and performance in which life cycle cost was emphasized and cost effectiveness optimized. Consequently much more extensive design, increased rigor and systems engineering and documentation was emphasized in this new process.

More specifically the Navy would develop the concept formulation in which the performance criteria and requirements were established and would then selicit from industry contract submittals. Based upon the Navy's specifications industry would draw up a contract design and production plan more commonly referred to as the contract definition. Out of a half dozen designs the Navy would select the "best" and award a contract for construction of the entire package at a fixed price.

Once again however as in the conventional process serious problems existed with the CF/CD process because it was too risky. More specifically there was just not enough control over industry by the government with so much "out of house" design. Also and more important the entire acquisition process was stretched out to 10-15 years and consequently had severe problems in technology changes and obsolescence. As an example the DD1052 class program which began in the mid 60's experienced modernizations and conversions on the vessels built at the beginning of the program before the keels of the last ten were even laid. This was due to the extremely lengthy design and construction process of the CF/CD phase.

One thing that stands out as probably the most important aspect of this process is the recognition of the ship's life cycle cost. Previously with performance optimization design life cycle cost was a low priority item. However with the shift towards more expensive payload and platform systems, higher maintenance and operational costs, it was obvious that since acquisition cost only amounted to about 25% of the life cycle cost that much more attention was needed in the later cost rather than the former. This was basically accomplished by performing a life cycle cost effectiveness study on the vessel's sub-systems as an aid in the trade off decisions. The life

cycle costs would be reduced as a result of the expensive analyses under taken during the contract definition process and the introduction of series production. Furthermore, related costs such as training and repair part support, would be lowered by ship standardization. Such items considered were reduced manning through automation, decreased repair, modernization time and maintenance costs, test and evaluation of sub-systems prior to installation, crew training, spare part systems, and RMA analysis. In essense it was obvious to the Navy that since a majority of its budget went to keeping its ships operational rather than building new ones; a large savings could be realized in optimizing life cycle sub system costs during the design phase, (Figure 13).

2.4 Present Approach

The CF/CD approach was deemed unsuccessful for the acquisition of naval ships and other major weapons systems and replaced by a new approach more commonly referred to as the "present" approach which incorporates several of the strong points of the previous two design schemes and also introduces several new concepts. The present approach incorporates the in-house design effort and multiple ship building of the conventional scheme with the industry participation (out of house), rigor of the systems

engineering, documentation, and cost effectiveness studies of the CF/CD scheme. However the "new" concept perhaps has the largest impact on the entire design process and that is what is known as "Design to Cost". The objective of his procurement scheme was to complete in little more than two years, all feasibility studies, a preliminary design and contract design; solicitation and receipt of "lead" ship proposals; all necessary contractor evaluation; "lead" ship negotiation; and contract award. Additional factors which contributed to the need for a new approach to ship acquisition were that Total Package Procurement in the CF/CD approach was experiencing difficulties in the Air Forces C-5 and the Navy's LHA. The conventional approach saw problems in frequently misunderstood or allegedly vague or impossible to meet specifications by the shipbuilders in addition to the lack of substantial time between "lead" and "follow ships and the low confidence in the firm fixed price" established at the time of the contract. Therefore the Design to Cost approach pushed for a strong "lead ship" approach by insisting that the time be extended between the manual "lead" and "follow" ship contract award. In this way construction problems could be exposed and rectified early and eliminated from "follow" ships. This construction approach is called "fly before buy", (Figure 13).

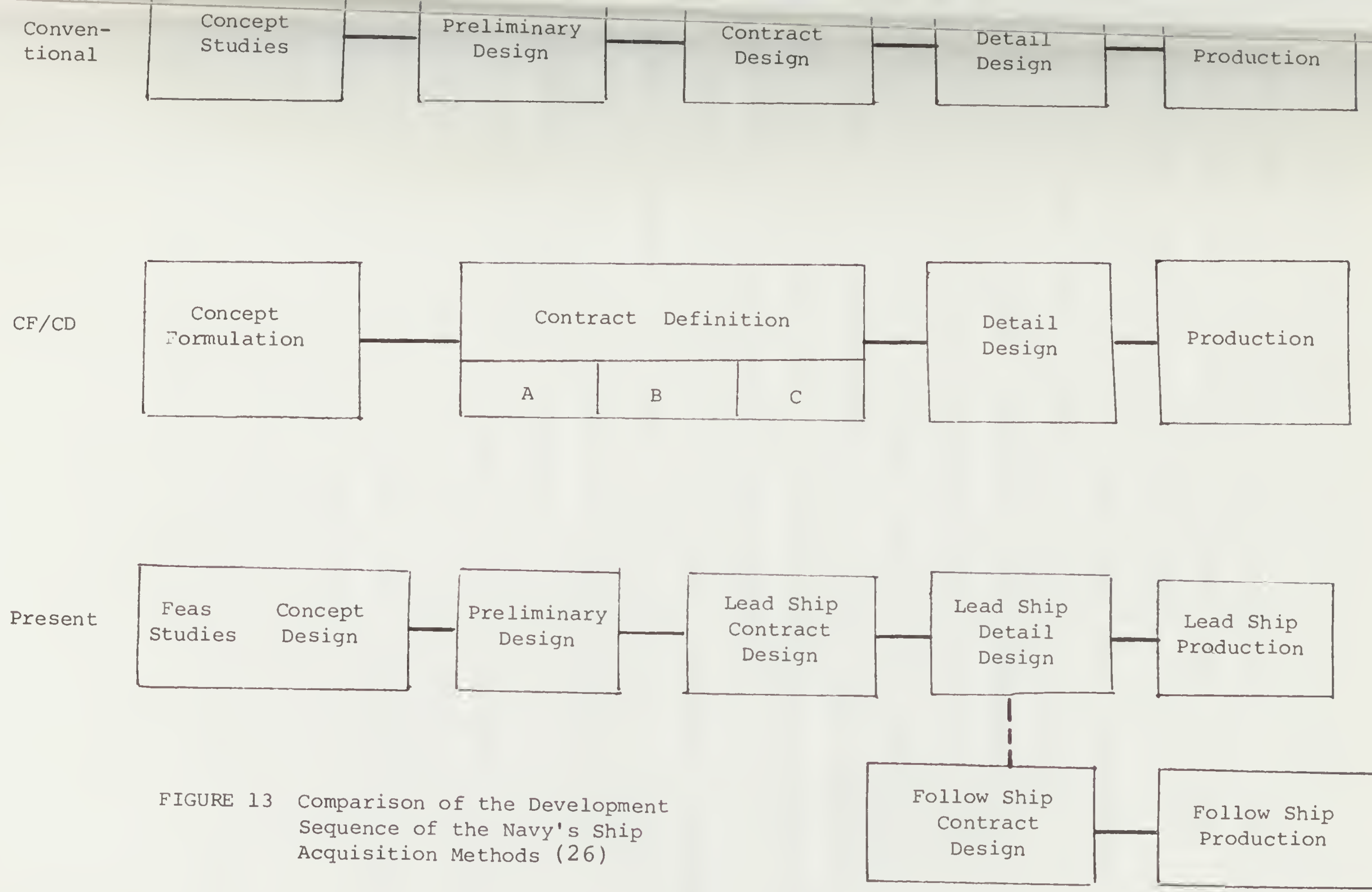


FIGURE 13 Comparison of the Development Sequence of the Navy's Ship Acquisition Methods (26)

Late in 1970 Admiral E. R. Zumalt, Chief of Naval Operations, that directed a study commence for a new ocean escort (the Patrol Frigate) to replace the aging WWII destroyers. Because of the large numbers required in a short time frame (by 1980), the total cost of the program had to be kept within reasonable bounds, and would therefore have limited capability but complementing existing ships of greater capability. More specifically the CNO established an average "follow" ship acquisition cost and a full load displacement as contraints not to be violated. The design was to proceed in accordance with the characteristics and missions, but capability was to be "traded off" if it appeared that either of these constraints would be exceeded. In effect these constraints required the development and implementation of an entirely new philosophy of Naval ship design.

The ship designer needed to have a design philosophy to guide him in making the trade offs and compromises which dominated the design process. Two issues which required guidance involve the relative importance of performance and cost and the selection of which cost to be utilized in the design trade offs. For the DF program the following guidance was established, (23), (24), (25).

1. <u>Performance/Cost Trade Off</u>

"There must be a willingness to trade off desired performance to achieve the cost goals while assuring that a viable weapon system design is obtained".

"A design to cost program should be implemented which prevents funds being spent beyond the point where costs rise rapidly for small increments of increased performance reliability. Although the Design to Cost concept does require cost, schedule, and performance trade offs, minimum essential performance requirements must not be sacrificed".

2. <u>Acquisition vs. Life Cycle Cost</u>

"Unit production test must become a primary design parameter. But this emphasis should not be construed to imply that the unit cost is the sole driving consideration in systems acquisition. Acquisition costs reductions must not be achieved at the expense of increased ownership costs".

"DTC is not a license to trade off operating and support costs for reduced acquisition cost".

The objective of the Design to Cost concept is to hold down the acquisition cost of weapons systems. It's concept was first established as a formal policy in DOD directive 5000.1 in 1971 as follows:

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"Cost parameters shall be established which consider the cost of a acquisition and ownership; discrete cost element (e.g. unit production cost, operating and support cost) shall be translated into "design to" requirements".

This guideline is directed to increase the cost consciousness of ship designers and acquisition managers and thus hold down the cost of ships. However, the problem remains of determining the fine distinction between minimum essential performance requirements and excessive performance capabilities. In addition the guidance implies that the designer must achieve a balance between acquisition and life cycle cost although it does nto specify which has priority. However, there is little doubt that the immediate visibility of specifying a constraint on unit production cost and the reality that initial budget requirements are established for acquisition cost will result in ship acquisition cost receiving the greatest attention. Thus, Design to Cost is an attempt to hold down the unit acquisition cost of ships so that the Navy can afford to buy the number of ships required to maintain the required fleet levels. This concept seems to make sense however another approach to achieve the same end exists but by almost opposite means. That is to build a more expensive ship with a design philosophy of increased reliability, increased

availability and increased maintainability thus shifting savings in Life Cycle Costs into new construction. This concept will be pursued latter in depth.

2.5 The Impacts of Design Cost

The PF design proceeded under three mandatory constraints; cost, displacement and manning. The cost constraint required that the entire ship system be designed to perform a specific mission that augmented existing designs and just well enough so that the system was cost optimized rather than performance optimized within the given mission requirements. The cost reduction could have been brought about by one or all of the following means:

1. Reduced performance (cost = f(performance).
2. Take advantage of technology such as smaller lightweight components which results in low ship impact subsystems.
3. Improved management and rigorous design discipline to produce a tight design.

The constraint on displacement required close scrutiny of the ship's hardware needs and still meet the desired performance. This was established because it was easier to monitor weight rather than cost on a day by day basis. Therefore a sophisticated weight control system was necessary in order to properly allocate and budget weight between the various sub systems and equipment. Finally the manning

constraint required that manning be reduced through automation and shore site repair of various components. Reduced manning it was felt would reduce ship size and life cycle cost since approximately 50% of life cycle cost is operational expenses. The reduction in ship manning levels was forced by rising manpower costs, decreased defense appropriations and decreased availability of personnel. The rising share of the total Navy budget for personnel alone limited funds available for Fleet modernization and new ships acquisition programs. These increased manpower costs compounded the situation especially in relation to decreasing defense appropriations. The projected decreases, when considered with increased manpower costs, had the effect of doubly reducing budgets for Fleet operation, maintenance and modernization. While total military personnel have been reduced by about 1.2 million since 1968, military payroll and other personnel costs have gone up by close to $5 billion during this period. In a different perspective, fifty six cents of every defense dollar spent in FY 73 was for payroll and other personnel related costs as compared to forty two cents in 1968. Cost however was not the sole reason for instituting the manpower constraint in the PF design. An overall reduction and severe limitation in available manpower for sea duty has been projected due to the trend toward the all volunteer Navy. Recruitment and

retention problems are persisting in the face of high pay scales and accommodations to civilian life styles. For instance an extension of shore tours for career personnel has the effect of reducing the numbers of personnel available for sea duty. Therefore every aspect of the manpower problem dictates a minimum level of shipboard manning in every new ship the Navy procures.

Although the reduced manning concept was a major constraint and because of its stingency very innovative maintenance strategies were designed into the integrated logistics support for the PF. Development of such an approach began with structuring the operational profile that depicted how the ship would be deployed and utilized at sea. This profile in turn was used to develop the PF maintenance concept which basically consists of off ship maintenance facilities and plug in type modules.

The policy of scheduling of component replacement before failure and off-ship repair of equipment is intended to reduce the maintenance work load of shipboard personnel. The concept is mainly directed towards electromechanical equipments which dictates the need for rotatable pools. These consist of an inventory of spare equipments and components used to replace ship-installed units which have failed or are need of repair. Units that have failed are removed, refurbished and placed in inventory. For smooth and successful operation the concept also requires that

the design provide accessibility for equipment removal and replacement to a far greater degree than has been required for previous ship designs.

The second portion of the reduced maintenance concept consistes of the replacement after failure of equipment modules and "off-ship" repair of inoperative modules. This strategy is similar to the first, except that the modules for replacement would be stocked aboard ship as an integral part of shipboard space allowances. This applies mostly to the electronic equipments.

Finally in order to achieve greater than normal at sea utilization the maintenance concept also calls for the elimination of regular overhauls and replaced with Intermmediate Maintenance Availabilities (INTMAV) at approximately six month intervals and Restricted Availabilities (RAV) at approximately two year intervals in lieu of the 36 to 39 month interval for regular overhauls. This "progressive overhaul" is intended to reduce the off line time of the PF. In addition the regular cycle for ship modernization was eliminated and replaced with the military Improvement Plan which calls for installing SHIPALT and ORDALT packages during INTMAV and RAV. Obviously combining all three constraints was quite difficult because all three tend to drive the design in opposite directions. For instance increased automation reduces manning but increases

weight and cost, decreased weight through lighter materials increases cost, etc.

Although the PF is the only "Design to Cost" vessel that has been carried through to contract and construction there are some striking observations and comparisons to be made in relation to non DTC ships.

To begin with the FFG-7 (PF) is the only single screw gas turbine powered ship which means high HP/wt. ratio. It carries a manning level of 181, a significant reduction over past designs, in fact a 30% lower manning level ratio.

From a weight allocation standpoint the FFG-7 shows marked differences in payload weight fraction with about a 20% decrease from past designs. This is primarily due however to low weight density payload items and not a significant reduction in payload carrying capabilities over past designs. Other weight groups show no significant differences.

The FFG-7 carries comparable payload volume however there is about 15% less space allocated to personnel. This can be attributed to the reduced manning levels, however becuase of the increased importance on habitability the space-man ratio has increased. The decreased living space is perhaps offset by the increased allocation to passageways and access which is required for the maintenance by replacement concept.

The FFG-7 has actually more internal volume than its predecessor, the 1052 class, but displacing 500 tons less. This lower ship density is due to the previously mentioned items of high HP/wt ratio, increased habitability standards, low density payload, and more access space. In essence the FFG-7 is larger but lighter than any of its predecessors.

From a military mission standpoint the FFG-7 cannot be considered to be a highly versatile multi-mission warship, however, it can be considered to be a significant addition to and an increase in escort and sea control capability of the fleet system. This is how the FFG-7 was designed under the DTC concept. It is therefore difficult to compare its military effectiveness against previous designs because of the wide range of capabilities required for multi-mission warships.

One item of performance that is strikingly different and blatantly obvious is the ship's ability to "support" its military mission and mobility capabilities. This characteristic is focused in the RMA of the ship system. A ships operability is vitally important; in fact, a ship which pocesses performance capability and mobility but unable to be crew maintained is not an effective design.

The FFG-7 shows high risk in this area of support due to its low manning levels and lack of future growth capability. With its manning cut by 70 men over the

DD 1052 the question arises whether the FFG-7 can accomplish facilities maintenance such as cleaning and preservation within Navy PMS standards. Certainly one could not expect to believe that an FFG-7 would require less house cleaning, painting, and hull maintenance or have in general less wear and tare than any other ship. From fleet experience, the most demanding manning situation is most often peacetime import and not wartime condition I or III at sea.

The lack of future growth capability is reflected in the cost cutting measures of reduced or elimination of service life margins. The FFG-7 does not have as much flexibility to accommodate new systems when it comes time to modernize the ship. This "tightness" is contrary to the modularity design philosophy in which subsystem flexibility is emphasized in return for speedier and easier modernization, improved military effectiveness and reduced life cycle costs. The FFG-7 comes closer to the Naval Architects limits than has been found prudent in the past.

It is the contention of this thesis that the DTC philosophy in holding down ship acquisition cost has seriously impared any future growth capability which represents a reduction in not only the ship's present performance capability but also its future capabilities. Perhaps a warship's greatest threat is obsolescence which is brought about by changing technology, state of the art,

nd enemy threat. A warship must be designed and built so hat it can keep pace with technology and incorporate the atest and more sophisticated payload items and other omponents quickly and inexpensively. Otherwise the ship ill probably cost more over the life cycle.

"The fundamental question which must be asked is hether this pressure imposed by this DTC philosophy esulted in a tighter and thus more efficient design which an still carry out the required mission or whether the bsession with reducing ship size and cost resulted in a hip lacking in basic capability", (9).

It seems ironic that the advanced concept of reduced n board maintenance and off-ship repair of inoperative nodules was brought about by a severe limiting constraint n the design. The PF design shows great strides in the direction of modularity and measured availability, however, it is this authors contention that the latter case in the above observation exists. The PF appears to be lacking in basic capability because of the philosophy of "Design to Cost". In order to explore the full potential, benefits and flexibility of a module design, the design philosophy has to be changed from DTC to something like "Design to Change".

3. Design Considerations for Increasing the Navy's Return on Investment

.1 Introduction

The fundamental question in Naval ship design at this pint is whether limited capabilities and flexibility be the ey point with acquisition cost receiving the highest priority nd life cycle costs secondary or whether a slightly more xpensive ship be designed with increased capability but with he sole aim of reducing the overall costs of keeping the ship urrent and afloat. It appears that the most sensible means ould be the latter, however, as the saying goes, "it's easier aid than done". It is similar to the situation of a car buyer rying to decide between an inexpensive compact or a luxurious ercedes Benz. In the one case the purchase is relatively cheap oth in price and perhaps quality. In the order, if the buyer an afford to make the initial plunge then he can probably be ssured of decreased maintenance and operational costs, a longer ife and in the long run a less expensive investment. overnment investment for items of defense are somewhat more omplicated by the billions of dollars and the large number of tems involved in the acquisition process. The basic concept, owever, is still valid.

.2 Reduced Life Cycle Cost Through Reduced Acquisition Cost

Essentially there are five components which add to he total cost of acquiring and operating a naval ship for lifetime of 25-30 years. These include design, acquisition,

aintenance, modernization, and operation (Figure 14).

Obviously there are many ways and combinations of having various components in order to reduce the life cycle ost. However, one must be cautioned to the pitfall of elieving that reduced expenditure in certain areas naturally ranslates into decreased ownership costs. For instance, he design effort in terms of length and participation could e reduced, however, if the design is not tight then the ntire package could be lacking in performance and may not ven meet the design requirements. The entire design is herefore useless.

One means is by concentrating in the acquisition area hich in essence is what the present "Design to Cost" hilosophy does. This makes sense for two reasons. One is hat this is the second largest "piece of the pie" and avings in this area are probably more than those possible in he design area. The other reason is that because of the iscount factor a dollar received today is worth more than ne received at a later date. Therefore, savings realized arly in the acquisition process are worth more than an qual savings realized in the operational area of the hip's life at 10-15 years of age. However, if too heavy an xe is used in making an austere vessel then most likely he design team has run into the previously mentioned itfall.

In Chapter 2 it was brought out that the PF was esigned with an acquisition cost, displacement and anning constraint, and austerity being the key. The final roduct was a vessel whose performance capabilities were ot overly impressive by itself but filled an important ap in the "fleet system" by augmenting or supplementing he planned and existing fleet of escort ships. The PF as intended to operate with other escorts and if these xisting escorts possessed an adequate capability in a ertain area then it was felt that the PF need not uplicate it. This seems to be sound philosophy however ne must look at the impacts of this philosophy before assing judgement. As brought out in Chapter 2 the PF showed high risk in the area of support due to its low manning levels and lack of future growth capabilities. The first item may be manageable but the later would ppear not to be. Because a Naval ship is exposed to frequant technology changes and a high rate of obsolescence for items of payload, whose is to say that the PF will be able to accommodate these future changes during modernization periods if it has no future growth margin. If it is unable to do so then it can no longer supplement the fleet system and is therefore obsolite. Another possibility is that in order tc observe a no growth margin, manufacturers may be required to design super compact and light payload sub systems and components that may be installed in future modernizations.

his of course means increase modernization costs which robably translates into increased ownership costs.

.3 Reduced LCC Through Reduced Operation Costs

The second area where savings exist would be during the perational phase of a ship's lifetime which would include odernizations, maintenance and operationa. Because the perational portion is the largest, common sense says that this s where the greatest savings may be realized. Perhaps the wo major factors in this area are manning and fuel with anning having a far greater impact. In fact, the cost of man ower is an astonishing sizeable chunk of the overall cost hich is evident in Figure 15.

Obviously if an essentially manned ship can be designed hrough the use of automated subsystems and monitoring devices hen tremendous cuts in manning costs can be made. This is hat the PF attempted to do in imposing the manning constraint. owever, as previously mentioned in Chapter 2 extensive use of he manning reducing devices can increase acquisition cost and isplacement to the point where life cycle costs are increased. herefore, there is a trade off between the reduction in manning osts through automation and an increased acquisition cost. In ddition a decrease in manning requires that more shore based acilities and assistance be available in order to perform equired maintenance. This in turn requires that more components e of the "plug in, plug out" type. Depending on the extent to hich this is carried a cost reduction may result over the hip's life cycle.

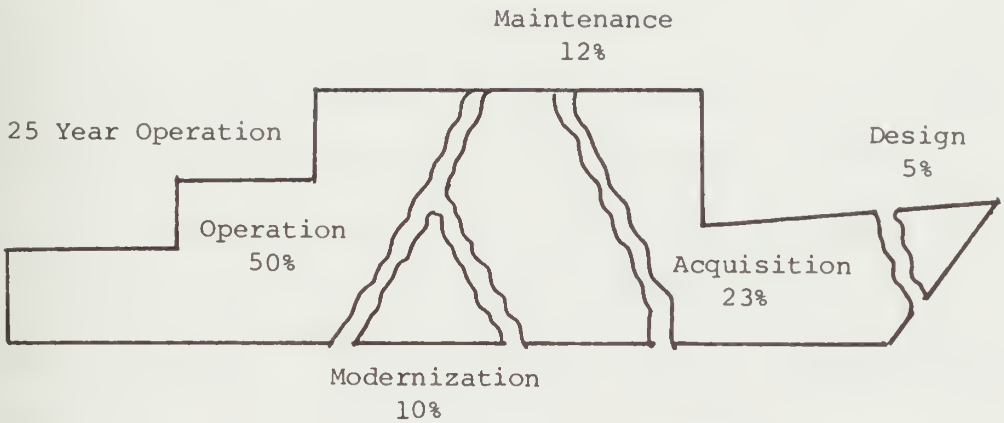


FIGURE 14 Life Cycle Cost Breakdown

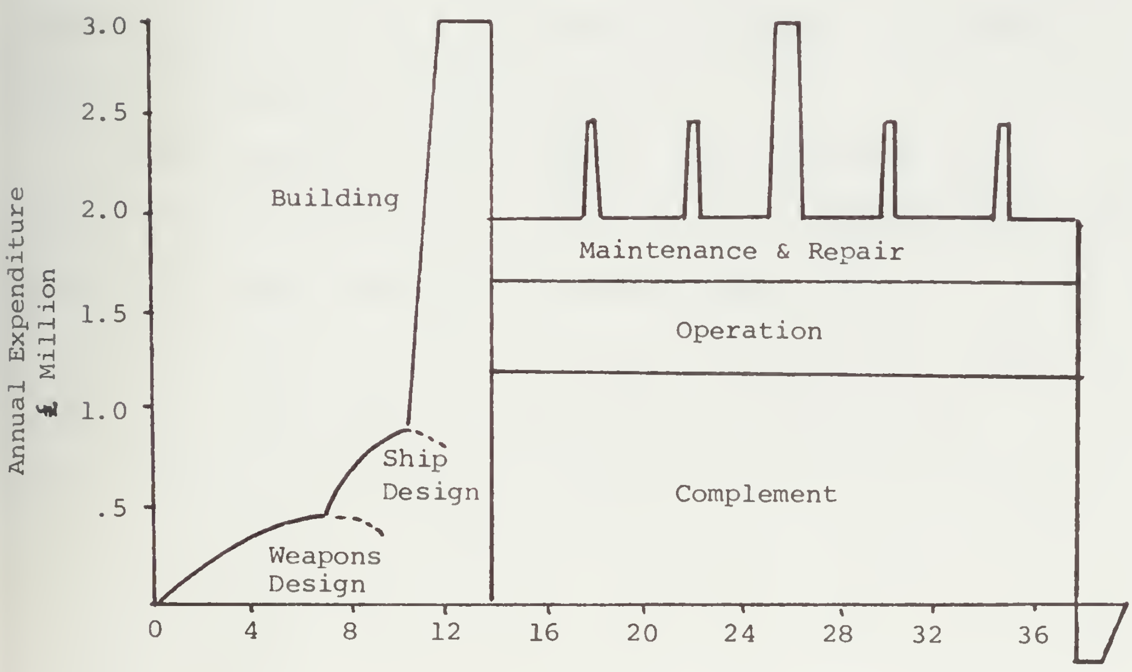


FIGURE 15 Life Cycle Cost Breakdown

3.4 Methods to Increase the Quality and Quantity of Ships

Certainly the cliche' "design is a trade off" holds for this situation in which several philosophies exist and seem to conflict. However, the "Design to Life Cycle" seems to make more sense when the Navy's ship acquisition is viewed as an investment and not merely as just another defense purchase. The investment must not be confused with that of the private sector, however, because the returns are significantly different. In the private sector investments are made with the idea of reaping monitary returns sometime in the future whereas in the public sector most returns are of a non-monitary nature that are non measurable. For instance a warship is intended to effectively carry out designed missions and performance capabilities in the line of national defense for a 25-30 year period. No matter which sector the investment is made the intent for both is to maximize its returns.

The investment of government expenditure in national defense consists of several areas which include new construction (SCN) weapon procurement (WN) other procurement, (OPN), R & D and T & E, and operation and maintenance. The return is measured by the military strength not only in terms of quality but also quantity.

Warship quality can be thought of as a combination of operational effectiveness or capability and operational availability which is a function of the system's mean time between failure (MTBF) (e.g. maintainability) and mean time to repair or downtime (MTTR).

Availability = MTBF/MTBF + MTTR

Capability can be further broken down into but not limited to the obvious items such as fire power, reaction time, payload carrying capability, etc. However, the element of time is also a function of any return and this perhaps has the largest impact on a ship's future capability. The factor of time must therefore be added to the weapon's value assessment. Capability is relative to that of a potential adversary and over the course of time an adversary may develop newer better weapons and/or develop weapon systems which are sufficiently different to negate existing defensive measures.

The Navy's job has always been the indespensable role of national defense but in recent years the Navy has been plagued by the inability of performing its missions. This is caused by the fact that the level of threat from foreign powers has steadily increased whereas the levels of U.S. defense has dropped to an all time low. This is caused by the fact that a slight shift has occurred in recent years away from surface combatant and ocean escort

acquisition to ballistic missile submarines as a sea based strategic deterrent weapon system. A consequent shift occurred in SCN budget to submarines away from surface ship construction. In addition because of the rapid rate of inflation the SCN budget has remained constant in terms of real dollars even though the budget has increased in terms of nominal dollars. What this all leads up to is that the Navy has not been able to build the number of ships it would like to with the performance capabilities it needs.

"Considering the ever increasing sophistication of hardware and software required to counter today's threats effectively, the gap between what is needed and what is available continues to widen." (10)

The problem, however, continues to get worse. Every one today is aware of the attacks of congress and the public on the defense department to trim its budget and cut otu the frills and unnecessary expenditures. In addition, with the removal of US. involvement in S.E. Asia, the emphasis on government expenditure has shifted from defense to more vital areas of natural concern. Therefore, it appears that an increased SCN budge is unlikely and because today's weapon system are becoming outrageously expensive just to meet basic performance criteria it appears that only solution is to shift the emphasis from more dollars

or defense to more defense for the dollar. In doing so he Navy's return on the quality and quantity of combatant hips within the constraints of an essentially fixed overall udget is maximized.

With the identification of the two major elements, of ROI hip quality and quantity, the next step is to suggest eans by which they can be achieved. If a constant budget or the Navy is assumed then the only feasible means of ncreasing ship quantity is by either identifying cost aving measures and reallocating them to the budget elements reviously listed or by increasing the longevity of naval hips. Because new construction (SCN) is only one among ive elements in the Navy's total budget, it is the amount f this budget which determines the number of new ships that an be constructed. Therefore assuming a fixed budget the eans available of providing more funds for new construction s attained by the following means.

1. Shift funds to SCN from other Navy budget categories by realizing savings in the other categories previously mentioned.
2. Reduce the cost of modernization and conversion to free more funds for new construction.

3. Reduce the cost of new construction to allow construction of mcre ships - Design to Cost.

4. Increase the ship platform longevity.

The second parameter (e.g. increased ship effectiveness) s perhaps a little more difficult to quantify since it is irectly a function of time. As previously mentioned a hip's capability is measured relative to the rate of echnology change and to the capabilities of a potential nemy. A ship may be considered at the state of technology t the time of iniation of development however it if does ot undergo any modernization during its lifetime so that it emains at the state of technology then it experiences a eclined military value over time. At some point, which is ery difficult to pinpoint, the weapon system becomes obsolete. owever what is clear is that the onset of obsolescence occurs ore rapidly with faster rates of technology change and as ore advanced technology is available to a potential dversary. In fact, if one considers a weapon life span of 0-20 years and a development and production time of 5-10 years his leaves a useful life of 5-18 years before obsolescence. igure 16 is presented for observation of the facts just entioned.

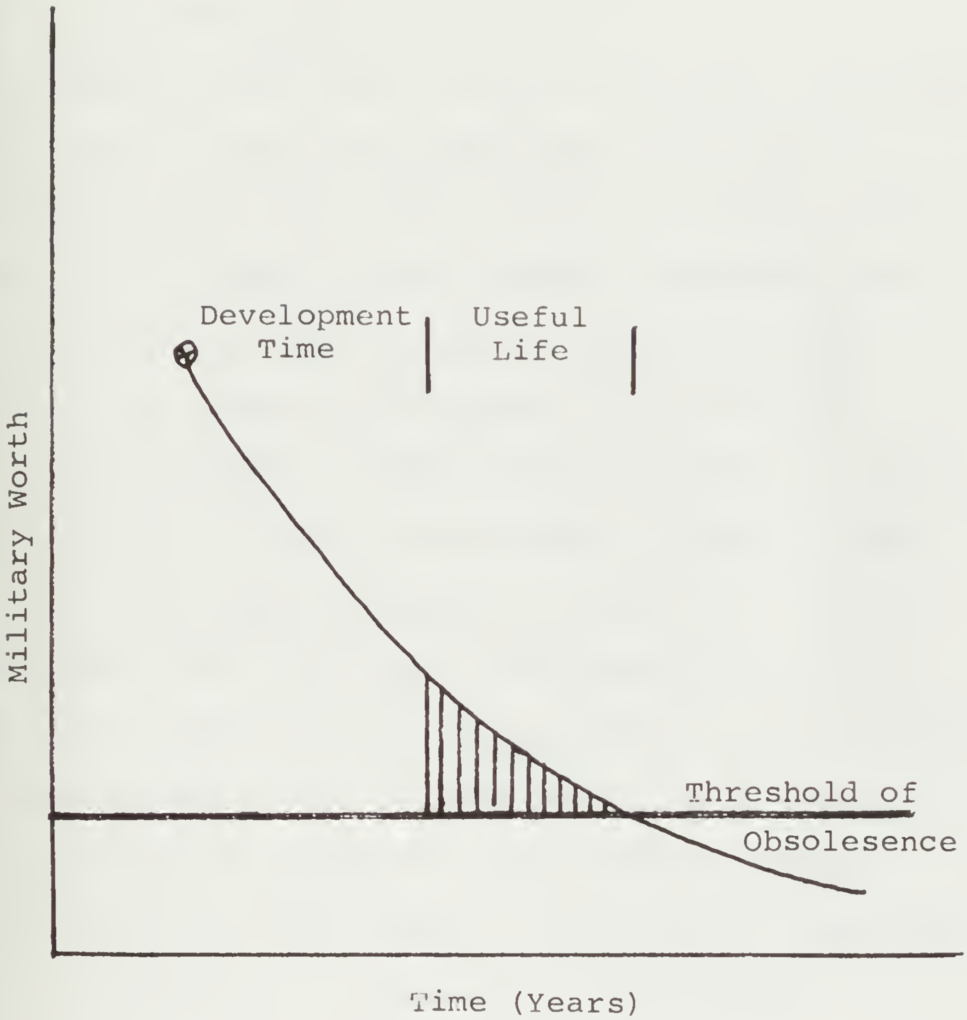


FIGURE 16 Military System Worth Curve

Chapter 1 attempted to explain the amount of design effort participation, and length of time required however some additonal comments on development time are needed in relation to military worth.

The problem that exists is that the highly formalized acquisition process pushes the development cycle out to about 14 years in which the combat system is proven in the first seven years followed by the platform definition and construction in the last seven years. Figure 17 is an illustration of the current time frame of the present acquisition process which includes design development, and service life up to its first modernization. The point to be made is that the lengthy acquisition cycle is caused by the requirement that sufficient development be done in the weapons suit so that reasonable accurate and well defined parameters can be established in the form of "Top Level Requirements and Specifications". This process however is perhaps a little outdated since it stems from a time when technology was changing at a slower pace and system integration wasn't such a difficult and time consumming process. The result is that due to inflation and the increased rate of threat and technology the platform characteristics have to be altered during the final years of development which in turn causes a complex and costly integration problem. Furthermore, the wide disparity of

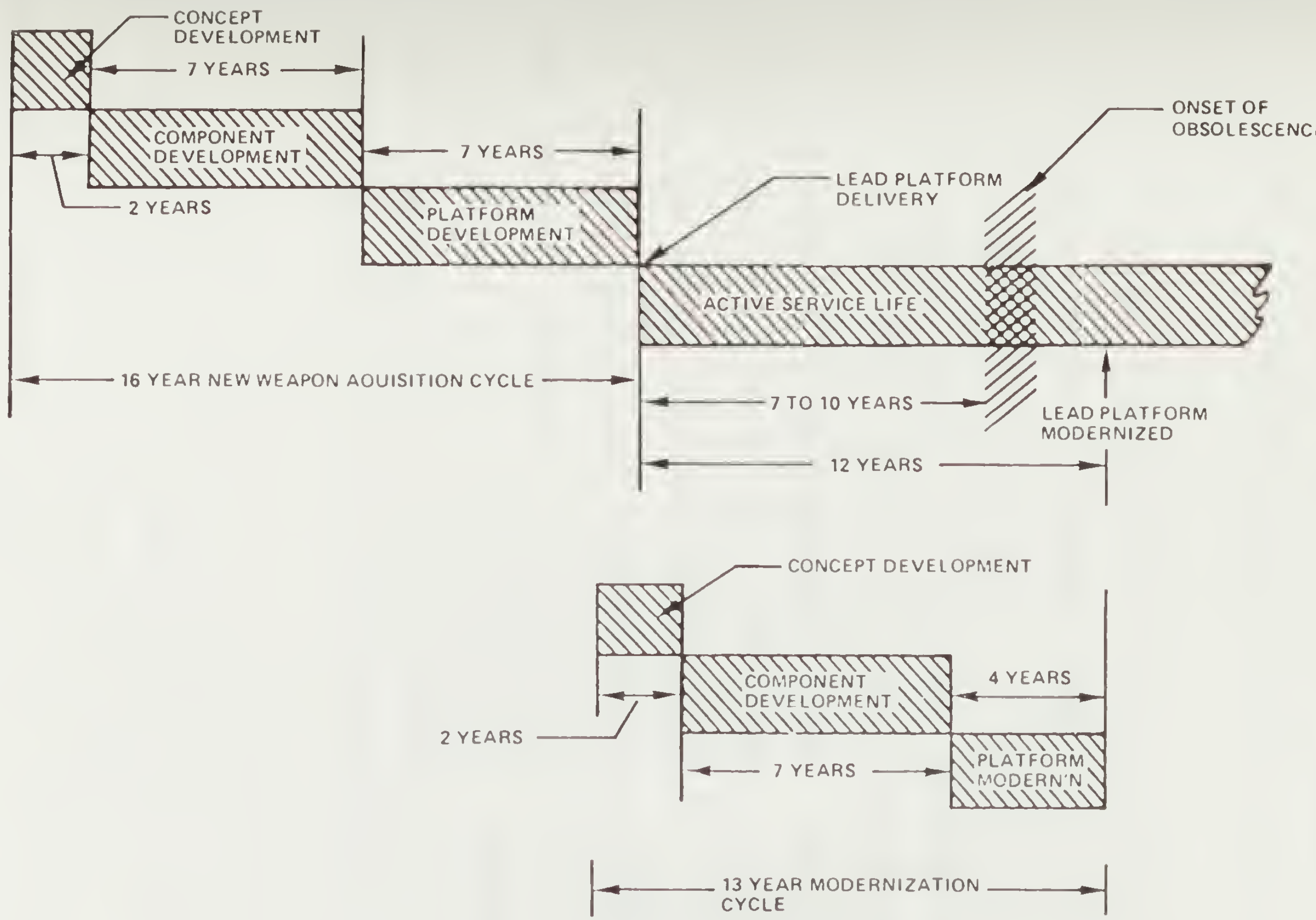


FIGURE 17 Current Time Frame of Design and Acquisition Process

obsolescence rates between payload and platform results in very costly and time consumming re-integration whenever a modernization is done. With this in mind the series development may be visualized in relation to the state of the art in Figure 18.

Finally the series development of payload and platform severely limits the useful life of weapon systems in comparison to a threat that is continuously changing. Follow ships will have an even shorter useful life than the leadship and it's conceivable that large multi-year procurements may result in the delivery of already obsolete ships. There are perhaps three alternatives to the above and they are to build short life ships and early disposal at the onset of obsolescence, build a static ship system for a 25-30 year period or make periodic changes to keep the subsystem current with technology and the state of the art. Obviously the first one is cost prohibitive and the second is ridiculous which leaves the third as the only feasible solution.

"In an era when one speaks of technology having an ever decreasing half-life, it is submitted that one cannot afford the luxury of designing and building tightly integrated ships. To do so will hasten their obsolescence and reduce fleet effectiveness."[6]

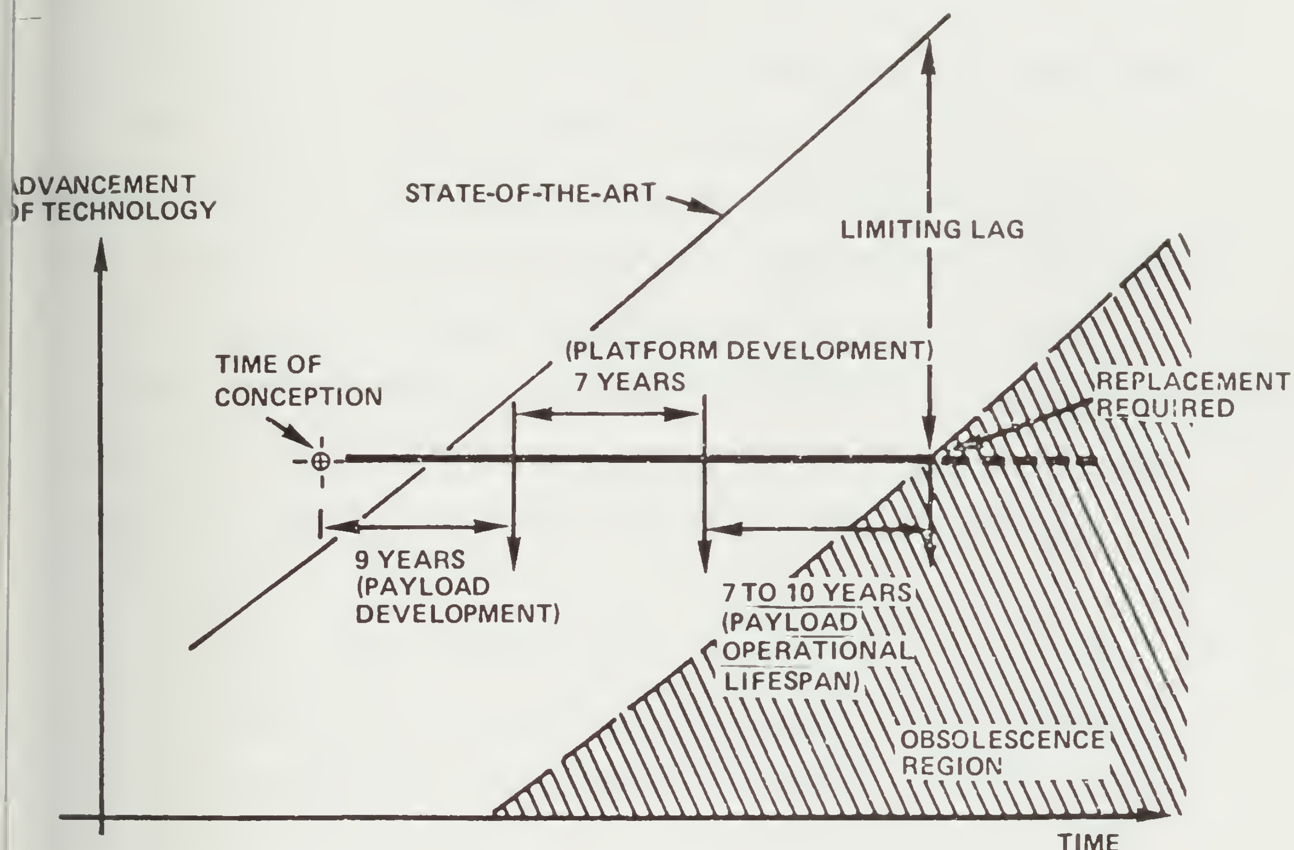


FIGURE 18 Series Development in Relation to the State of the Art (20)

The cause of the problem has been identified but feasible solutions along the lines of alternative 3 above (e.g. to increase the effectiveness of Naval ships) need to be established. For instance, if one considers availability as one measure of effectiveness then availability can be increased by raising the obsolescence curve or by earlier application of technology through the reduction of development time. This can be accomplished in three ways; 1) by increasing the absolute capability or performance of the weapon system, 2) by accelerating the advancement of the state of the art through increased emphasis on R & D and T & E, 3) by more frequent modernization; at a reduced scope and by limiting the modernization to crucial system components with the shortest technolical life span rather than exchanging entire systems.

The area under the Military Worth Decay Curve may also be increased by reducing the development time thereby increasing operational effectiveness by means of accelerated implementation of new technology. In other words what needs to be done is to cut down the time required for the series development and integration of the weapons payload and platform or if possible to pursue a parallel development.

A ship's availability is also a function of several items over the course of its lifetime such as the number and length of modernizations and regular overhauls, which require

approximately 20 months and 6 months respectively. Improving the ship's availability implies reducing the amount of time the ship is unable to perform or only partially able to perform its intended mission. Figure 19 presents an approximate availability scenario for a conbatant. With four RDA and one M & C in a 25 lifetime then the best availability that can be expected disregarding emergency repair and yard availability is about 85%. Therefore in order to improve availability and the ROI, four alternatives exist:

1. Decrease the time required for modernization and conversion.
2. Decrease the time for regular overhauls and restricted availability.
3. Increase the component reliability
4. Increase component and system maintainability.

With this in mind it appears at this time that the means at hand to increase both the quality and quantity of ships, their effectiveness and the overall ROI is the concept of modularity -- "Design for Change".

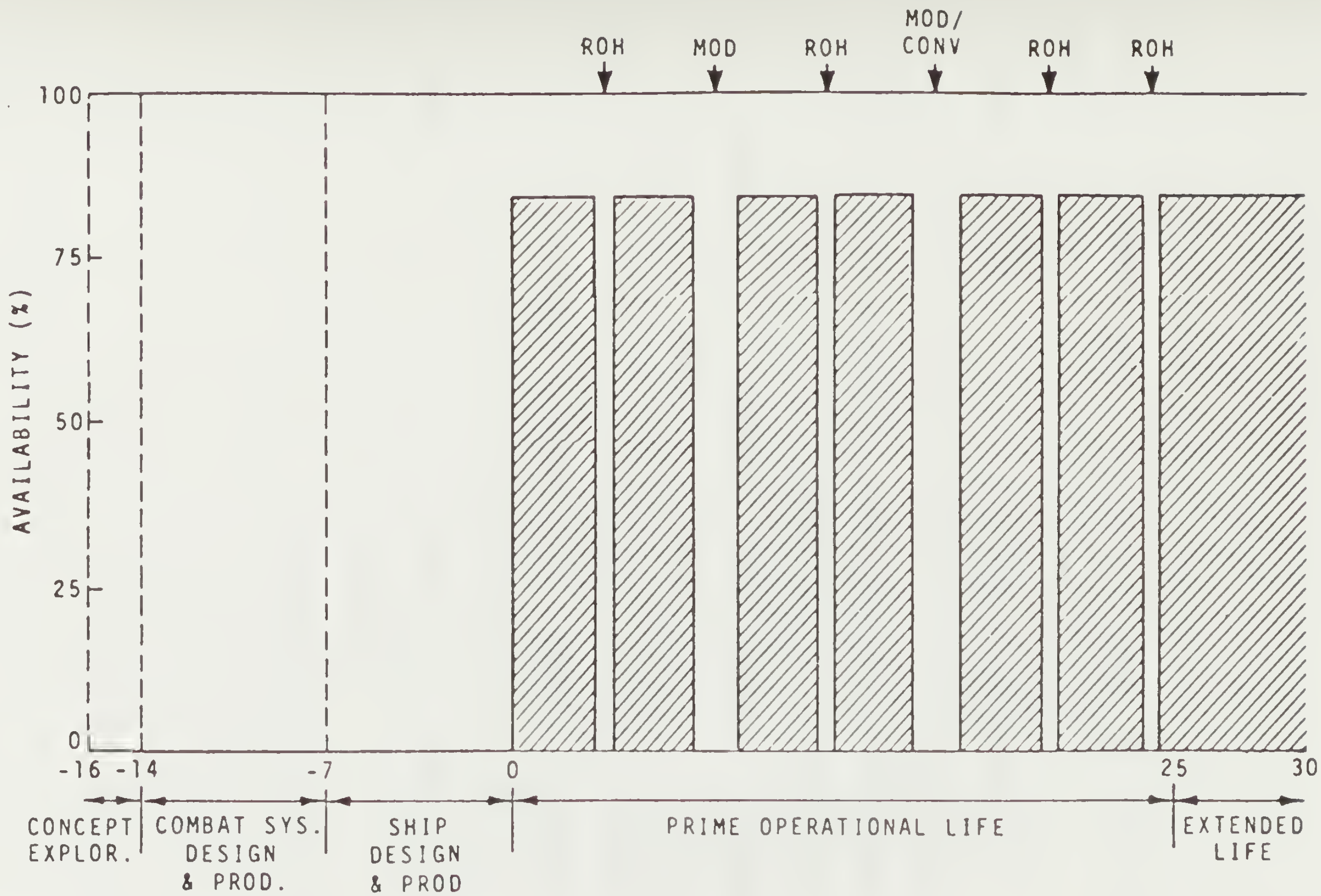


FIGURE 19 Approximation Operations Profile for a Combatant (6)

4. Design for Change - The Modularity Concept

.1 Definition of Modularity

As outlined in the previous chapter there exists two listinct yet interrelated problems of designing a ship so hat the platform is essentially uncoupled from the payload nd a ship design so that future conversion can be ccomplished with relative ease. The first problem may ot be completely solvable because there are no simplistic nswers to combatant ship platform and payload integration roblems or even to component or subsubsystem integration to orm the combat subsystem or payload. The fairly new concept f modularity however is a partial if not complete solution o this problem and is a definite solution to the problem f accomplishing easy future conversions. Before showing ow this can be accomplished the modular concept must be lefined, its present state of art presented and some of he concepts that have up to now been studied.

Not everyone has the same understanding of the meaning f modularity because the word basically lacks precision. he American Heritage Dictionary contains the following rray of definitions: 1) a standard, 2) a uniform component sed repeatedly in erection or construction and 3) a self ontained assembly of components that perform a specific lass of tasks in support of the major function of the rimary object.

In ship design and construction one must not erroneously hink of modularity as only containerization which is merely narrow band of the overall concept. The broad band definition o be kept in mind is the physical and/or functional grouping f elements of a complex system into building blocks for the urpose of 1) ease of construction, 2) ease of integration,) ease of installation, 4) ease of removal and 5) ease of nterchangeability. In ship design the work modularity has een used to identify anything from large, sometimes pre utfitted segments of ship hulls to an assembly of several ieces of equipment mounted on a common pallet, to throw way circuit cards, to a subroutine of a computer software ystem. In this study the word modular shall be defined as: re-packaging of a collection of equipment (systems or omponents) for the purpose of their assembly and check out rior to delivery to the ship for installation and removal f the package. The modular design as proposed by a Booz llen[3] study is a system constructed of modules or unit ackaging scheme, usually having all major dimensions in ccordance with a prescribed series of dimensions and which re capable of being easily formed or detached as an entity rom other components, units or next higher assemblies. nder this broad intrepretation it appears that the term pplies to all procured and pre-assembled or nearly "ready o install" equipment packages such as gunmounts, launchers

and directors. However it is not limited to any specific category of ship material i.e. hull, propulsion, electrical, electronics payload.

4.2 Module Types

The above definitions provides a basic understanding of the concept as used in this thesis however it is necessary to establish some basic levels of modular design in order to categorize various types of modules. The three classes of modules that presently exist are construction, large scale functional and small scale functional modules. These are basically distinguished by both size and utility.

4.2.1 Construction Module

The construction module includes large scale, pre-outfitted sections of a ship which are joined together to form the total ship. This concept fits the modular definition however detachment at a future time at the module connections is not anticipated but still remains possible. Piping system, ventilation systems, electrical wiring and various forms of detail work may be completed and checked prior to joining the modules. This technique allows for construction of large sections of a ship and a substantial portion of outfitting done while compartment accessibility is still good. Later all the sections are joined in a drydock or building platform. This technique

is only limited by the lifting capacity of the yard equipment, material available, fragility of the installed equipment, pilferage and imagination. The net reduction in time spent by the ship at the building site in finishing work and in outfit after launch yields lower overall construction costs and production time. This process is well suited for a series production such as that undertaken by Litton in constructing the LHA. Jumborized hull sections that have been constructed and outfitted in assembly line fashion are joined into a single ship unit. The intent of the construction module is solely to aid in the production phase and not for future modification and maintenace. Few ships have been designed with the intent and possibility of reopening in the future.

Construction modules reached large scale applications during WWII as "package construction" in order to reduce the time for construction, conversion and repair. Some specifics include the prefabrication of hull sections and production line assembly of liberty ships and "jeep" aircraft carriers; installation of blister envelope and 40 m gun sponsors on old battleships; and prefabrication and installation of new bows on battle or storm damaged destroyers and cruisers. Present day use in addition to the LHA program include the installation of jumbo hull sections an the Manhattan and Navy submarine construction;

pre-outfitted hull sections in Japanese and Swedish ship construction; tanker pre outfitted sections in the Brooklyn Yard of Seatrain Shipbuilding; preassembled helicopter hanger and mast structure for the 692 class destroyer FRAM; preassembled deck hosues for Navy and Merchant Ship construction.

The construction module shows great promise and benefit to the shipbuilder in the way of reduced construction time and costs which can be passed on in part to the operator as a one time saving in the acquisition cost. However, this module type has very little impact on the problem of payload/platform uncoupling and ease of future conversions. In addition the subsystems in the construction modules are generally highly integrated which requires the opening of many subsystems during module separation to gain access to one.

"Although past and current shipbuilding practices employ extensive planning of the constriction program to maximize the amount of off-hull assembly and test work, the objectives of the packaging schemes are essentially oriented to the reduction of cost and time required to construct and test the ship and seldom are optimized to satisfy the user's needs during the operations phase of the ship's life cycle." (3)

4.2.2 Large Scale Functional Module

The next level of module type is the large scale functional module which are packaged units that perform a major function and are as large as one or more ship compartments. Such items as a missile launcher, magazine handling equipment and fire control electronics may be contained in a weapons module while a command and control module may include CIC, radio room, electronic repair shop, electronic component spaces stowage and conning station. Basically this level can be thought of as a mission module which when used in a series production provides for rapid modernization and conversion assuming the modules can be easily removed and replaced.

Large scale functional modules have been employed in recent years in three categories; 1) the single location integrated subsystem, 2) one or more compartments, 3) single location integrated systems. For instance the contract proposal for the LHA included incorporation of four interchangeable weapon modules. The 1960 DEG study recommended a fully outfitted electronic compartment carried in a pipe framework for checkout and testing ashore prior to installation aboard ship in one crane lift. Multiple compartment modules have been utilized in the containerization of both organizational and intermediate

maintenance functions and supply support for the SH3 aircraft on the USS WASP. Containerized avionic workshops were installed aboard the USS Guam in order to analyize the Sea Control Ship containerized AIMD design concept. Similarly the USS America was outfitted with three specialized equipment containers to support EA-6B aircraft.

4.2.3 Small Scale Functional

The final class of modules consists of the small scale functional modules and has probably received greater attention in recent years than the previous two types. These modules are useful primarily in conducting maintenance and repair and are generally small in relation to the size of the ship. Such uses include printed circuit boards, gas turbine hotsections and frequency changer sets. Small scale modules seem to be best suited for high failure rate standardized items where quick and easy removal and replacement is necessary. Present uses include combatant weapon and launcher systems such as the 5"/54 raped five guns, MK 26 missile launcher, ASROC, Sea Sparrow and Terrier MK10 missile system. These systems are installed as a unit, connected to ships systems and finally checked out. The FBM submarines utilizies a modular grouping of the GMFCS MK 84 which can be installed in minimum time withreduced on board testing. Finally the latest nuclear powered surface ships have special superstructure design

features which allows for easy vertical removal and replacement of fuel cores and reactor plant equipment. The building block may be considered as an extension of the pre packaged module and the small scale functional module and allows for the enhancement of capability through the simple exchange, addition or deletion of a module to the basic configuration already installed. It allows for modernization and conversion of the component level instead of the system level, given that the modernization involves simple additon or reduction to capability that already exists.

The representative modular systems presently in use are summarized below: (10)

CATEGORY	EXAMPLE	WT - TONS
Construction	1. Jumboizing Hull Sections	X1000
	2. Pre Outfitted Hull Subassembly	200-600
	3. Pre Outfitted Deckhouse or Assembly	200-600
Large Scale Functional	1. Single Location Integrated System	50-100
	2. Single Location Integrated Subsystem	1-200
	3. DNG or More Compartments	10-50
Small Scale Functional	1. Component Assemblies	1-50
	2. Components	1-10
	3. Parts	.01-1

In summarizing, modularity in the shipbuilding industry has been used quite effectively since WWII by developing construction modules of hull, deckhouse and specific compartments with the effect of decreasing both the shipbuilding cost and time. The Large Scale Functional modules permit ease of checkout, installation, repair and refit at reduced time and cost. The Small Scale Functional items permit ease of repair and refit.

It should be obvious at this point that modularity is more than just pre-packaged units or a pre-assembled grouping of a number of related things in a common container that are dropped on board a transport vehicle, are easily moved about and are easily removed and replaced. The fact is that this is only a small portion of the concept and that full consideration must not only be given to the module but also to the transporting platform and to the interfaces between the two.

There appears to be extensive experience and knowledge in the different modular groupings, however the change in the methodology of ship design and construction has been slow because the modular development up this point has been more the result of necessity and not of a new design approach.

Another contributing factor is the trend toward the integration of shipborne systems particularly in the combat

systems which makes it increasingly difficult to identify subsystems which can be physically separated into individual module. For instance many electronic and weapons systems require auxillary services such as A/C, fresh water, hydraulic power and certainly electrical power. In addition many of the ship's subsystems have no central location but are scattered in parts within the ship for reasons of operational need and efficient use of space. This of course prevents a functionally coherent package.

Perhaps a better reason to explain the slow progress towards large scale modularity is the lack of in depth studies to date. Basically past attempts were too broad and therefore unable to answer some of the specific questions. Others addressed only specific cases which included insufficient and nonconvincing generalizations. There was insufficient effort in these studies in analyzing the all important difference between technical feasibility and economic feasibility. Finally studies were done in the context of a specific ship system development program, thereby tying the study group into the overall ship concept development program schedule wherein the necessary technical development was precluded in time for that program, the program funds were insufficient or the technical risks were considered too high.

"It seems apparent that future warships will apply as much of the modular philosophy as technology will permit. A critical element in the wider use of these modular techniques in the Navy is a recognition of the potential and then a movement to develop modularized mission oriented payload." (6)

4.3 Reduced Acquisition and Life Cycle Costs

The basic question at this point is how does the modular concept alleviate the problem of an insufficient number of surface ships. As mentioned in Chapter 4 this can be accomplished by either increasing the budget for new construction and build more new ships or by increasing the availability of these ships presently in service or a combination of both. The modularity concept can increase the pool of funds for new ship construction by shifting funds from one or several of the other budget categories. It appears that the various features of the modular conept could contribute to substantial savings in the budget categories WPN, O & MN and OPN. More specifically the building block design and the standardized component allows standardization for a broad range of applications between ships of the same class and between other classes. This allows for bulk and multiple purchases. As a result an approximate unit savings of

8-17% per category could be realized with a minimum purchase of 5 shipsets. Because most new class purchases are many times larger than this minimum the inter class standardization should produce even greater savings. Thus the building block or small scale functional and standardized components in the combat system should reduce required funds in the WPN category. OPN could also be reduced if the approach were extended to mechanical and electrical systems in the platform. Additional savings could be expected in manning costs (O & MN expenditures) due to the reduced maintenance man hours brought on by the improved system reliability and maintainability. The increased R & M stems from the ability to replace high failure modular components with progressively improved components without otherwise impacting the basic system. This approach is represented by the present NAVELEX Standard Hardware Program.

The second means brought out in Chapter 3 to increase the new construction fund is to decrease the cost of modernization and conversions. Because of changing threats and technology changes M & C will always be necessary. To do otherwise would mean ships that are well behind the state of the art and forced into early retirement. The fact is however that since 1953 M & C

costs have continued to comprise 20-25% of the SCN budget. A closer examination of M & C performed on 15 different ships breaks down the cost into the following: (6)

Category	% of Basic M & C Construction
Hull Modification	36 $\pm$ 3.5
Ship Services Modification	32 $\pm$ 3.5
Combat System Rip-On and Installation	28 $\pm$ 4.8

The cost of changes to the platform, payload and their interface were pretty much equal. Where the expense comes in for most M & C is that major structural modifications and changes to the arrangement of non-structural bulkheads are necessary due to the lack of initial space and arrangement provisions for weapons system changes. In addition the refit involves replacement of one weapon system with a completely new and different one; consequently no components of the system being removed are common to the replacement system. Very often the existing auxiliary services do not have enough built in margin to handle the increased demands brought on by the new system and therefore have to be upgraded.

It is this area where modularity perhaps has the greatest impact since the concept is oriented towards accommodating future changes in mission requirements --

"Design to Change". It offers reduced funding requirements for M & C by utilizing modular combat systems, a platform configured for ready installation and containment, access and service connections and simple interfaces between payload and platform, and thus allows more money for new construction.

The third area of cost savings is through the use of modular sections during the construction phase of ship design. As previously brought out the pre-outfitted hull assemblies in commercial ship building reduces construction time and cost. This savings can be attributed to five key features: 1) "ideal" working conditions with easy accessability, 2) parallel assembly activities, 3) Test and checkout accomplished in parallel with construction and prior to installation, 4) learning curve effects from pre assembly of many identical similar items, and 5) ease of handling and installing fewer, pre assembled units. The large scale pre packaging need not however be limited to the construction phase. In fact, similar savings and features could easily be extended to the development of weapons and electronics. Simplified interfaces through consolidation and elimination contribute to the ability to parallel test and checkout prior to installation; that is an essentially independent module. Parallel

testing is also facilitated through such features as service trunking, access routes, distributing centers. These also allow for those GFE components and subsystems with long lead time delivery to be installed later on in the construction phase thus eliminating the governments risk of contract delays due to late deliveries. To a large extent the shipbuilder's schedule can be made independent date of the delivery if items of payload and any late changes in the makeup of the payload can be handled with the built in provisions. It even appears feasible to have the weapons and or C3 subsystems assembled and tested by the prime contractors, delivered to the ship and installed after construction is complete. In spite of a possibility in increased internal volume the net effect is reduced construction cost of new ships, in addition to reduced construction time and a more rapid influx of new ships into the fleet. Although reduced construction costs seem feasible, studies by Booz Allen Applied Research in 1968 show that the acquisition cost is actually increased. Depending on the amount of modularity employed in the design significant costs were realized in the one time cost items of subsystem and equipment development, detailed engineering, construction and test facility equipment, crew training, ship materials

nd equipment. For instance in the subsystem development hase more design effort would be necessary if interhangeability of dissimilar subsystems is contemplated. lso if major emphasis is to be placed on lowering shipoard maintenance skills requirements and manpower reduction, ignificant costs may be required for development of more mall scale functional modules. Most of these cost ncreases however are for one time costs which occur at he start of a multiple construction project. If the esign calls for a large number of vessels to be built hen these costs can be spread out over the entire project nd make the increased development costs appear insignificant. n any case more analysis is required to determine the xact impact on acquisition cost.

.4 Increased Operational Effectiveness

Perhaps an even greater impact of the modular esign than on the construction and acquisition stage is he ship's operational effectiveness. The improvement n this area is achieved by five elements.

1. Reduced combat system development time.
2. Reduce ship platform development time.
3. Parallel development of platform and payload
4. Reduced modernization and conversion time.
5. Incremental, more frequent modernization at the component level to reduce the military worth decay rate.

Previous chapters brought out the increase in echnical complexity, design effort and cost involved in eveloping today's advanced combat systems which is ttributable in part to over-centralization. With the eature of component standardization in the modular esign, interface problems are simplified in addition to ecentralization via direct functional mechanization. tandardization also allows reapplication of proven omponents that may be employed in the new system with little dditional development affort.

In a similar fashion the time required for platform onstruction is reduced through the use of construction odularity. The more efficient working environment, he use of pre outfitted sections and the shift from a eries type construction in a drydock to a parallel one n building platforms all adds up to faster ship onstruction. As pointed out, these advantages are generally ell recognized and most modern shipyards make extensive se of construction modularity.

The third aspect of increased operational effectiveness is an offshoot of the first two and is one of the biggest dvantages of the modular design. The payload/platform eries development is presently a 12-14 year process. Obviously a payload system that is considered state o the art at the beginning of the design is certainly

:lose to obsolescence or in need of modernization in today's :echnology pace soon after the first ship is delivered to :he fleet. The Military Worth Decay Curve illustrates the ;ubstantial losses involved in the series development. 'his problem is further compounded in a large construction ›rogram extending over a period of 9-10 years. A ship's reapon suit could become obsolete before a ship of the ;ame class, but later in the series, is delivered which .n most cases leads to modernization and conversion of ;ome ships concurrently with new construction of others. 'igure 20 illustrates this exact problem that faces the)E 1052/DE 1978 class.

Assuming that the payload/platform interfaces are 'irmly established and pre-negotiated and firmly adhered :o, modularity has the potential to permit parallel levelopment of payload and platform and avoid the risk lue to concurrency. In this way a combatant can be designed nd delivered to the feet in almost half the time. This, f course, increases the shaded area under the Military 'orth Decay Curve, increases the operational effectiveness nd the ROI.

Ease of modernization and conversion and the reduced ime involved is perhaps the most widely publicized and dvocated reasons for the application of the modular

oncept. The worth decay curve not only applies to new onstruction but also to an existing ship awaiting a ew weapons suit in a M & C which studies show has an verage duration of 28 months. With the judicious balance f modularity featues, interface simplification and mproved integration methods significant time savings re likely.

The combination of decreased development time, & C time, (overhaul, maintenace, and repairs time) aturally adds up to greatly increased ship availability hich means a decrease in the amount of time a ship is ither not available or only partially capable to perform ts intended mission. The present operating profile f a Navy combatant approximately consists of four regular verhaul periods each of six month duration, and one odernization and one conversion requiring about twenty onths each of all which fits into an operational lifetime of 5 years. For these figures an "off line" time of at least wenty percent is expected if one also considers the fact hat the ship is still only partially available as the esult of reliability (MTBF) and repair (MTTR) problems. Therefore a combatant availability of 85% is considered realistic if not optimistic.

The inprovement in availability can best be illustrated in Figure 21.

It is assured that extensive use of modular concepts can reduce off line periods by as much as 50% (i.e. M & C requiring 10 months vs. 20 months) which boosts average system availability to 95%. In addition availability is further extended by increasing the life expectancy. This is accomplished by replacing the high failure rate building block type submodules with more reliable units and leaving the basic more durable segment of the system intact. It should be pointed out that the above illustration and figures are more of a goal rathern than fact. However, the improved availability is considered achievable.

The last element of increased operational effectiveness is that of incremental M & C. The present approach to upgrading weapon systems is to wait until the entire system is obsolete. If regular interval updating of key components in the system most prone to obsolescence, significant higher Military Worth is achieved, As illustrated in Figure 22 the useful system life (shaded area) under system replacement is substantially less than that of incremental modernization at the component level. Very often in any payload system the rates of obsolescence of its various components are all different. Therefore replacement of these components as they become obsolete rather than waiting until all the components in the

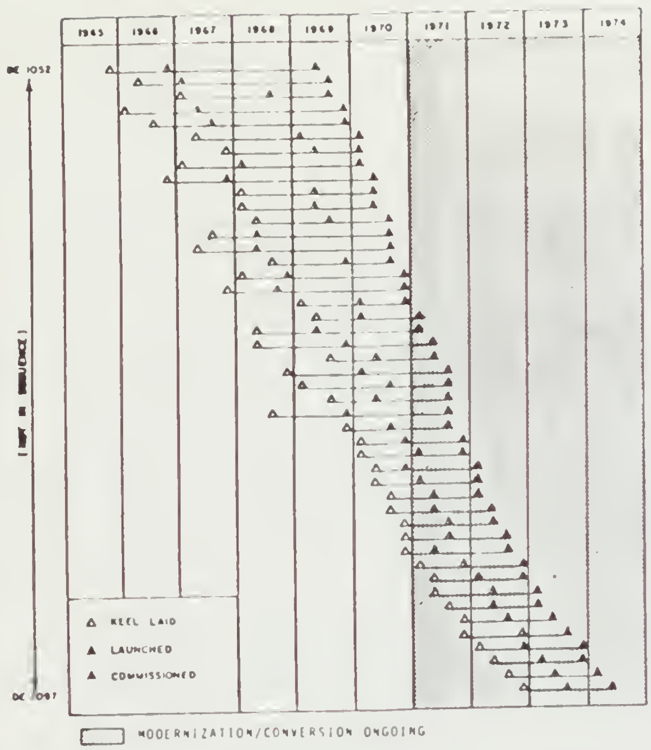


FIGURE 20 Modernization and Conversion Overlapping Construction of Large Series (6)

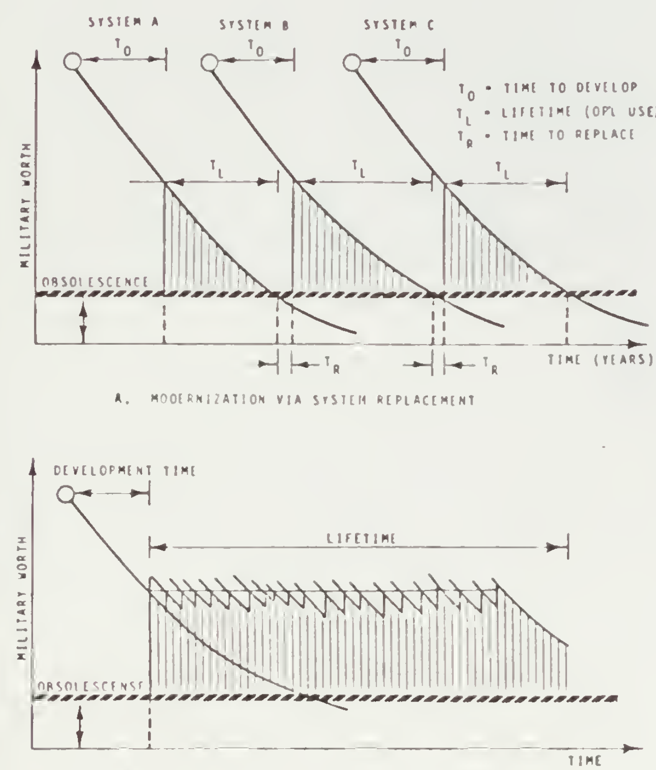


FIGURE 22 Incremental Modernization Power to System Obsolescence (6)

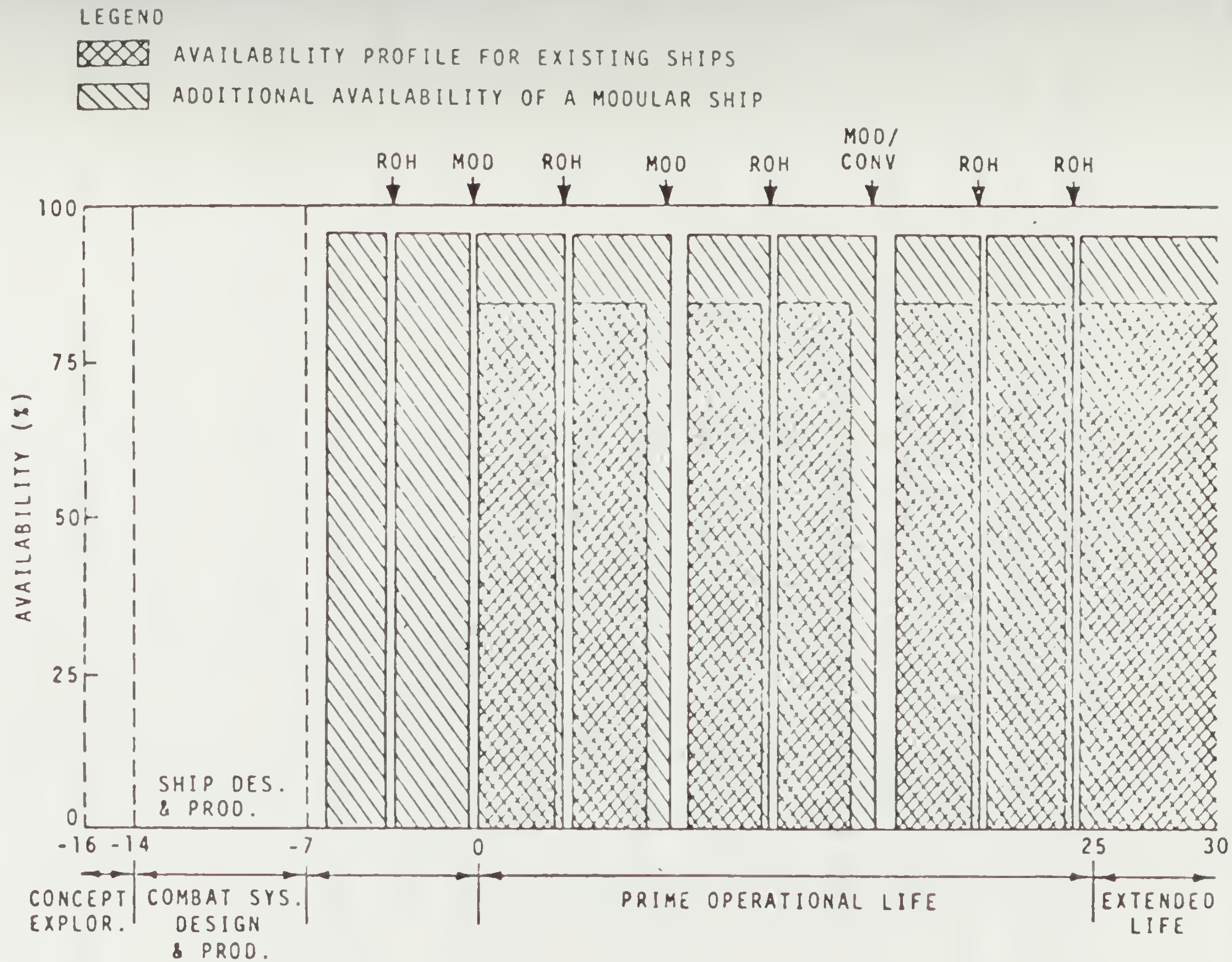


FIGURE 21 Availability Scenario, (Approximate) for Modular Design (6)

ystem are obsolete makes more sense. However this can only e achieved if the initial design of a system adheres to he philosophy of "Design to Change" down to the component evel.

.5 Imapct on Ship Design Acquisition Cost, Volume, Wt.

Early studies investigating the costs and benefits f modular ship construction show that practically all the ajor ship's characteristics (cost, volume, displacement, eight) are impacted. These studies also indicate that ost benefits are possible if certain penalties are illing to be incurred; the biggest being increased cquisition costs for new construction. The National ecurity Industrial Association in their modular study oncluded that modular combatants cost approximately 4% more han conventional ships. However because of the greater vailability of the modular ship, NSIA went on to show hat 83 ships would do the same job as 100. Thus, there s an acquisition cost savings of about:

$$100(1 - 1.04 \times 0.83) = 14\%.$$

avings in personnel and maintenance would lead to decreased ife cycle costs which is where the true payoff is to be ound.

Perhaps the major reason for increased acquisition ost is the necessity for greater internal volume resulting n larger ships compared to conventional types with ission effectiveness held constant. This increase has een estimated to be seven to eight percent. Simply roviding space margins for future systems is not sufficient f the platofrm is to be truly adaptable to change; the onfiguration of space provided is important. Also a eans of trunking services to the module are desirable and rovisions for module shipping and unshipping routes must e carefully designed. Clear access to platform areas n which modules are located are important becuase time nd cost savings are very much dependent on clear shipping nd unshipping routes. In addition, the removal and nstallation of module should have little if any effect n surrounding structures. A final point to keep in ind for internal volume and topside accessibility is that irect vertical movement of modules is more easily chieved than lateral movement.

The second contributor to increased acquisition ost is the increased displacement of the modular ship hich shows up almost entirely in the hull structure wt. group 1). This increase has been estimated at about %. On the SCS for instance hatches and access requirements dded structure in descrete jumps as each successive

deck was penetrated by modularity. In addition the increased volume and displacement increases the gross characteristics (length, beam, draft) of the conventional design. This in turn impacts powering requirements and fuel weights.

The complex interface problems between modules and between modules and platform is perhaps the largest obstacle and challenge to the modular ship designer. The interfaces in most cases demands arrangement changes and perhaps relocation or deletion of certain invisible areas. Shipping access must be provided for each and every module for rapid removal and installation however many cost effective uses of modularity are often located deep in the hull such as sonar gear, chill and reefer spaces, etc.

As previously mentioned the changes to ship systems most likely occur with mission related or payload systems and therefore a motivation exists for clear payload/platform distinction and separation. However this separation in design is clearly contrary to present day destroyer design in which emphasis is placed on tight system integration for the sake of volume economy. The separation is further complicated because most of the "support" systems fulfill dual functions in supporting both platform and payload. For instance a typical destroyer's combat system accounts for 50% of its acquisition cost yet only 25% of the enclosed volume and 10-15% of the light ship weight.

The support services however for both payload and platform surpass the payload weight platform cost and both platform and payload in volume. The crucial question left to the ship designer in modularizing the payload subsystems is deciding whether support systems should be considered as part of the platform or as part of the payload.

The designer must also be concerned with module compatability. Configuration compatability between the replacement module and the ship platofrm installed site must exist. Also designated modules and platform locations must have entity characteristics such as weight, center of gravity shock resistance, environmental requirements, etc. Compatability of operation and support service interfaces between modules and between module and platform is another consideration the designer must face.

Finally the designer has to address the actual hardware of the interfaces. The efficiency in installation, removal and exchange of modules is a strong function of the interfaces between module and platform. These interfaces may be simplified by several means such as buffering through the use of adaptors which however is considered to be a brute force type method. Standardization simplifies the exchange of one module for another and eliminates the need for adaptors and connectors. Consolidation reduces the number of module that must be buffered or

tandardized. Finally complete interface elimination ould be the ultimate in simplification but carries with t an increased cost. This would be accomplished for nstance by having a weapons system complete with its own uxiliary services.

.6 Miscellaneous Areas of Impact

Fire is still the chief cause of damage to naval hips today and modularity unfortunately does not alleviate he situation. In fact, fir and flooding constitute he prime risk areas of modularity. Fire and flooding oundaries cannot be established around the modular ontainers because they cannot be economically built to ithstand fire and flooding. However large scale functional odules such as weapons and magazines can be made watertight nd fire resistant by fabricating a total enclosure of steel r shielded aluminum. Containers of non metallic materials ose their structural integrity in a fire or give off oxic gases and are therefore undesirable. Finally the abor and expense of providing certified DC penetrations nd openings for access would not be justified.

.7 Summary

In Chapter 4 the concept of modularity as it applies o ship design is defined and the different levels of

modules are established. Also previous uses of modularity were discussed however most of these were related only to the construction phase of the ship. The fact remains that the concept has barely been scratched at eh surface. The need still exists to improve the modernization and conversion of major combatants not only because of the increasing amounts of time and money necessary to modernize ships, but also because of the frequency of necessity to do so. This need can only be met by a new liberal approach to ship design and imaginative application of modern technology. The design approach of modularity is intended to reduce overhaul periods, thus precluding excessive ship costs related to non operational time.

Several Navy programs are in the development stages at present that recognize these ships design needs and the benefits associated with modularity. The Seamod Program (SEA Systems MODification and MODernization by MODularity and Inter MODularity) is intended to address the question of modularity by a comprehensive approach which considers the opportunity for pre packaging and factory checkout, as well as methods to reduce the ship input overhaul period by developing containerized payload systems. The intent is to shorten inport ship time by reducing ripout and installation time. Naturally, there will be decreases in ship usable payload weight and volume and an

increase in the budgetary and planning process. However the ROI should clearly be in greatly reduced life cycle costs and increased availability.

In order to meet the changing threat SEAMOD emphasizes the need for rapid and continual fleet modernization. The modernization costs may well increase but the goal is to decrease the cost associated with dead import time for crew and ship. Seamod also requires a clear functional distinction and definition of power, water. The proposed benefits of the SEAMOD concept are: improved affectiveness, reduced modernization time and costs, more efficient use of personnel and accelerated innovation in research and development.

The ARAPAHD concept is one of several modular concepts being considered to supplement conventional Sea Control forces by providing merchant ships with their own indigenous defense. Its principal aim in container standardization and configuration is to develop the capability to readily adapt ARAPAAD modular payload to a range of host ships without the need for costly and impractical changes to structure and hull fittings. Four basic areas of the concept are: the host ship, the ASW helicopters, the Navy flight crews and support personnel and the series of modular vans containing aviation support and maintenance equipment.

The Navy's Test and Evaluation Ship, another concept still in the early stages, attempts to conduct test and evaluation of new shipboard systems and equipment in a realistic environment. Its major features include the capability of rapid refit, ability to conduct parallel testing, commonality of test support facilities and platform dependability. These features however depend on extensive use of modular concepts including checkout of modules prior to shipboard installation. In addition, maximum flexibility is necessary so that new test payload candidates may be accepted with minimum modifications. Extensive use is made of existing quick-acting interface connections between test payload and platform.

Changes to a naval ship over its lifetime are a virtual certainty. These changes are brought on by one or a combination of the following reasons:

1. Changing threats or inability to correctly forecast the threat.
2. Changing defense priorities.
3. Evolving technology.
4. Deteriorating systems as a result of physical wear.
5. Changing design philosophy such as habitability regs.

6. Correcting design deficiencies or construction.
7. Correcting erroneous decisions made at the time of concept development.

Therefore, future navy ships must be designed with the idea of change in mind so that a more rapid means of up-dating shipboard equipment at periodic intervals not associated with shipyard overhauls, thus extending the overhauls cycle.

The modular design concept appears to be a viable solution to the problems the Navy faces with its ships however life is not quite so easy. There are still many questions and issues which need addressing. Two such critical issues of importance are the resolution of figuration compatability to minimize the impact of module exchange on the ships and the necessity for standards for interface connections Navy wide. It appears that the only way to resolve the above and provide a final assessment of the exact costs and benefits is by brute force. In other words, a separation of payload and platform must be performed in an actual design at the expense of planning and budgeting dollars as well as hardware procurement and ship volume. However this additional initial investment should be more than offset by a decreased life cycle cost. The major reduction in

operation life cycle costs show up in manning costs which are as mentioned in Chapter 3 the most significant life cycle cost. Also the navy faces the problem of fewer people for sea duty as a result of the all volunteer service. With the increased application of the small scale functional modules both these problems can be partially alleviated because manning skill levels should be reduced appreciably.

Modularity exists in many forms from the construction sections and large scale functional units down to the plug in plug out circuit boards. However the intent is not to propose using all the features all the time but to propose judicious selection of that combination of features that maximize the benefits derived under the contraints at hand. The problem is to determine the degree of modularity which is best and the extent to which it should be applied to new ship designs -- modularity -- to what extent?

5. MODULARITY DESIGN APPROACH

5.1 Establishing the Need

From Chapters 3 and 4 it is obvious that the judicious use of modularity in ship design has far reaching benefits which appear somewhat to solve the many problems facing the Navy with their combatants. These include reduced availability becuase of lengthy M & C, spiraling costs of new acquisitions, reduced funds, and man power shortage just to mention a few. Obviously the Navy desires to extend modularity as far as possible beyond the present state of the art. However, the designer is faced with several major questions which need addressing. The first is how much modularity does the Navy actually need in their ships? The easiest way to answer this at present is somewhere between the present state of the art and the technically infeasible range. The designer needs a simplistic methodology to aid him in selecting a level of modularity which represents the best trade off between the benefits he seeks and the increased acquisition cost. However, before the designer can address this problem he must first know the actual costs and actual benefits that are derived with each module in his design. In addition he must be able to identify the point at which modules become technically infeasible and the point at

hich they became economically infeasible. This, of course, equires an extensive quantitative cost-benefit type nalysis.

.2 Cost Benefit Methodology

Because a qualitative model for determining the xact impacts of the expanded use of modularity goes far eyond the technical capabilities of this author a design ethodology utilized by industry in the Navy's DX/DXG program hall be briefly outlined.

The designer first of all must establish some basic roundwork in order to get him headed in the right direction. his can best be accomplished by establishing a frame of eference consisting of two basic features.

1. The establishment of levels of modularity.
2. The identification of technical and management considerations which may be constrain the application of modularity to a ship.

.3 Establish Levels of Modularity

The designer in this methodology is not so much nterested in the many construction package techniques. lthough they provide time and cost benefits during the onstruction period they do nto really qualify as "modules"

unless they also incorporate provisions which facilitate ease of renewal.

However, the modules are not limited to a specific category of ship material (such as hull structure, mechanical, electrical or electronics) or level of application. Therefore to facilitate an orderly and comprehensive study, the modules, as suggested in Ref. 3, should be divided into two broad categories: physical envelope (ship structure) and equipment units. Each of these are broken down into four sub categories so that all possible module types are fully convered. These include:

1. <u>Physical Envelope Category</u>

   P-1 A major section of the ship structure or superstructure.

   P-2 A group of spaces within the ship structure or superstructure.

   P-3 A single space within the ship structure of superstructure.

   P-4 A unit appended to the ship or superstructure which changes the basic envelope of the ship - a podule.

2. <u>Equipment Unit Category</u>

   E-1 A major equipment grouping (e.g. propulsion subsystem, navigation subsyste, weapon subsystem.

E-2 An assembly of components within one or more equipment groupings (e.g. gas turbine plus propulsion generator, air conditioning plant).

E-3 A total component (e.g. gas turbine or the compressor of a air conditioning plant.

E-4 Lowest designated assemblies - constructions of pieces for parts below the E-3 level.

.4 Technical and Managerial Considerations and Constraints

In determining the technical feasibility of the arious potential modular candidates the designer needs o keep the following technical factors in mind:

1. The physical enclosure module may effect the watertight and gas tight integrity of the ship. The use of the physical module could create additional avenues for egress of water or gas into the hull envelope.
2. In providing for removability of large modules, the structural integrity of the ship would have to be maintained. The strength of the ship's structure could be impaired by removal of major sections of framing, skill and/or strength deck.

3. A physical enclosure module would require structural integrity within itself. In addition to the requirement that each module has sufficient strength to permit its lifting and handling, it would have to possess sufficient rigidity to protect alignment of installed equipment.
4. Compatability of the weight and center of gravity of interchangeable modules would be necessary. Since the center of gravity and weight of the total ship is a composite of these items, any significant change caused by an exchange of the modules can have either anadverse or beneficial effect on the ship's center of gravity and stability.
5. Compatability of spatial configuration of related exchangeable modules is required, that is their size, shape and mounting must be similar.
6. The modular design would have to provide for easy removal and installation.
7. The design would have to accommodate the diverse, non-standard equipments and components available. Because very little standardization

exists among manufacturers a certain degree of flexibility of design is mandatory.

8. Concentration on large sized modules may de emphasize the benefits to be obtained from lowest level modules. The module design should take into consideration the need for fault identification quickly and simply by shipboard personnel. Numerical and skill level manpower reductions are predominately associated with the lowest level assemblies.

9. Design of modules would require compatability with the weight lifting capacity of building and conversion facilities.

Perhaps the most important managerial consideration is the anticipation of specific equipment changes during the design. Unless the plans for changes materialize little benefit could be envisage during the ships life as a result of a modular approach. However, if provisions for modular design can be provided which will facilitate specific alterations, significant benefits, in cost and time can be expected.

5.5 Net Worth Estimating Procedure

Once the designer has made a wide ranging search of all the possible applications and types of modularity and has weeded out those considered technically impossible, the economic feasibility must be determined on each of the remaining candidate. In order to properly assess the exact impacts of a particular modular over the ship's life cycle, the life cycle should be divided up into phases which are further broken down into segments.

The major phases of a ship's life cycle include the development phase, the investment phase and the operational phase. The development phase consists of such one time cost items as subsystem and equipment development, conceptual feasibility and preliminary design phase. The investment phase consists of:

1. detailed engineering
2. construction and test facilities and equipment
3. ship materials and equipment
4. ship construction and outfitting
5. ship testing
6. space parts - initial stock
7. crew training
8. operational support

Operational items include:

1. regular overhauls and alterations
2. unscheduled repairs
3. stores, spaces
4. manpower
5. fuel, oil

The methodology up to this point has been fairly straightforward, however, at this point it falls short because a valid measure of the affects of the application of modularity does not really exist because there is no or little accumulated data in the subject. What further complicates the matter is that the determination of modular cost and benefit impacts on the ship's life cycle assumes that the basic ship's life cycle cost is known. The fact is that only estimating procedures exist consisting of emperical relations to determine the various costs a ship experiences over its life time. The preferable means to measure the modularity net worth would be a precise numerical technique, however, at present no such measure is available. Present approachsdepend upon the judgement of the individuals applying the "tape measure". Therefore, because no rigorous method exists and because much technical expertise is required in this area, it does not appear necessary to outline the existing estimating procedures.

in addition for convenience in interpretation of results, it would be highly desirable to utilize a universally applied unit of value within the methodology. Since cost increases and savings are normally measured in dollar units, and since operational availability can be expressed as "military worth in dollars", the method should incorporate the conversion of all benefits to conversion value units-dollars.

5.6 Modularity Net Worth a of the DX/DXG Study

What needs to be brought out at this point are the results of the Booz Allen study (Ref. 3) for the cost benefit analysis on the expanded modularity use in the DX/DXG program. The measurements of these impacts, accomplished by implementation of the above methodology, was directly related to the postulated operational profile of any given ship. These were the baselines from which any charge generated by the use of modularity was calculated.

The major impacts were bacially in three areas: first of all an increase in life cycle cost mostly reflected in acquisition cost was estimated as 1% of the life cycle cost. Ship availability was estimated at 2.3%. Finally additional benefits which consisted mostly of increased reliability, and maintainability and reduced manning skill levels were estimated at 2.7%.

Once the designer has these figures for the most technically and economically feasible modular design, he must decide whether he needs this much modularity or will a lesser amount sufficiently meet his needs.

5.7 Suggested Techniques in Determing - How Much Modularity

5.7.1 Introduction

The previous sections of Chapter 5 outlined a methodology for determing that degree of modularity that is technically feasible in the present state of the art. It also analyzed the economic feasility through a cost benefit analysis of each technically feasible module on the various segements of a ship's life. The resulting design should be the most modularized vessel possible within the state of the art and still technically feasible.

The next question the design team should ask themselves is okay we have the most modularized design we can possibly get which costs us a little bit more to acquire but the increase in investment returns such as increased benefits (e.g. increased availability, increased maintainability, reduced manning skill levels and some costs reduction over the ship's life time) are much more. However, do we need or even want to employ this amount of modularity? Do we need this amount of increase in ship availability or can we settle for a lesser amount and do

we want to pay more for acquisition? This, of course, is a most difficult set of questions to answer for several reasons. First of the all design process does not consist of one person or even a small group of people but an extremely large combination of engineers, managers and operators both in the civilian and Navy community. Certainly in the design community there are many opinions on how much to modularize depending on each ones philosophy. The CNO may have one set of ideas or opinions on the subject, however, Congress who approves the Navy's budget may have different ideas. The taxpayer who ultimately pays for new defense systems may have a third set of opinions. Finally the overall design philosophy in vogue at the time has a major import on the decision. If performance is not absolutely necessary; if the level of enemy threat is relatively low then a DTC philosophy may be the design's driving force where acquisition cost is the primary concern and performance secondary. A full modularized ship with 95% availability may not be necessary. However, if the design stresses performance and mission effectiveness then a high degree of modularity and availability may be desired. To cloud the issue even further, the design community may envision many changes in the design philosophy and level of enemy threat from the time a ship enters the fleet until it retires. The obvious answer to this is to expect the

orst and design a ship accordingly, however, this is not lways economically feasible. What is needed therefore s a tool to aid the decision maker (e.g. design community, avy, CNO, etc.) in selecting a level of modularity which est meets his needs, desires and budget.

.7.2 Net Present Value

Chapter 4 presented the idea of Naval ship acquisition s an investment and discussed methods to increase the eturns on this investment. As in the corporate and private ector there are several management tools that may aid the nvestor (e.g. the Navy) in answering the above questions.

Several techniques shall be presented and analyzed to etermine their applicability and their advantages and isadvantages.

The first of these techniques is the *Net Present alue* method which is a discounted cash-flow approach to apital budgeting in the corporate sector. With the present alue method, all cash flows for a given investment are iscounted to present value using the required rate of eturn:

$$NPV = \sum_{t=0}^{n} A_t/(1+K)^t$$

K = required rate of return

t = year in which cash inflow or expense occurs

n = life of project in years

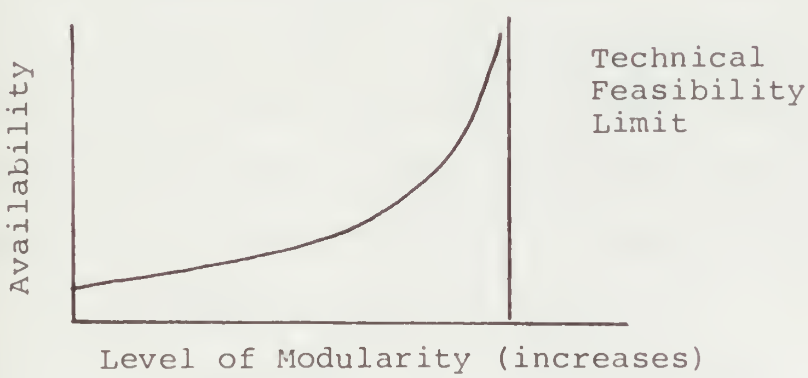
A_t = net of inflows and expenses in a given year.

If the sum of these discounted cash flows is equal to, or greater than 0, the proposal is accepted; if not it is rejected. Another way to express the acceptance criterion is to say that the project will be accepted if the present value of cash inflows exceeds the present value of cash outflows. If several projects are being considered then naturally the one with the greatest net present value will be chosen.

For the ship design problem several levels of modularity can be analyzed using the NPV method. The highest level would be the one which incorporates as many P-1, P-2, P-3, P-4, E1, E2, E3, E4 modules as economically and technically feasible as otulined in the proceeding methodology. Lower levels are considered those that incorporate fewer number of modules (e.g. fewer system and subsystem modules). The lowest level may be considered that one which incorporates just the state of the art modules. For each level the increase in acquisition cost is computed in addition to the cost savings, cost increase and increased benefits that occur over the life cycle of the ship. Each of these are discounted to present value. As in the corporate sector, naturally the level of modularity with the greatest NPV is the level to design to.

The method appears straight forward and easy enough but because of several assumptions and the

dissimilarities of government and private expenditures the method loses its usefulness. First of all it seems reasonable to assume that the greatest benefits are obtained with the highest yet still economically and technically feasible level of modularity. Increased availability is perhaps considered the biggest and most desirable benefit over the life cycle, however, most of the increase is directly attributable to the implementation of the higher level category of modules (e.g. P-1, P-2, E-1, E-2 type modules) which contain the payload systems and subsystems. This level of modularity is probably pushing the highest feasible level. The below graph is a rough approximation of the relation between availability and modularity levels, Figure 23.



lthough the acquisition cost is much greater at this level, PV would still appear to be greatest. This tells the esigner and operator not to worry about lower levels but o always design to the fullest extent of modularity.

s mentioned previously this decision is not always in line ith the ship design priorities.

A second drawback is that apples and oranges are eing mixed in this analysis. Namely the NPV method only andles cash flows or monatory units. Therefore, the nalyst is faced with the problem of converting such benefits s increased availability, increased reliability and aintainability, reduced manning skill levels, etc.into nits of dollars - needless to say not an easy task. lso, the analysis is only as good as the procedure or estimating the actual costs and benefits of the modular esign.

Finally the fundamental question and one which has een discussed and debated on in great length is what if ny discount rate should be used? In the corporate sector ne discount rate has a large bearing on the NPV of any nvestment to the extent that a slight change may switch ne NPV rankings among several candidates. The problem is owever, more basic becuase of the very nature of overnment expenditure especially on military defense nvestments. It is very difficult to justify even using discount rate let alone trying to select one. In the orporate sector the discount rate is considered the ost of capital that is utilized in funding a particular

nvestment. This funding may come from within such as its ash on hand and from an issue of stock, or from a bank oan or a combination of all three. The government on he other hand receives its funds from essentially one ource - the public. The government maximizing rate f one exists, however, has been estimated to be the ollowing:(2)

Interest Component	Rate
government borrowing rate	4.7
Less	
personal income tax on interest	1.6
Plus	
corporate taxes foregone	4.6
personal income taxes foregone	2.0
	9.7%

What negates the use of the NPV approach in the overnment sector is the non-marketable nature of the investment. he investment is considered non-marketable because ownership hares in it cannot be traded in the capital market .e. on the stock exchange. Furthermore, the U.S. government oes not operate at a profit. For ship acquisition the evenue of its investment is in the form of service to the ountry, therefore, service equals capitalization costs.

A vessel, however, does not have to operate at 100% availability to earn revenue. However, revenue (service) is lost, during unscheduled breakdowns and its scheduled yard availability. Because of these drawbacks, forcing the NPV approach into the government investment sector would naturally lead to erroneous results.

5.7.3 Internal Rate of Return and Payback Period

Some may argue that the Internal Rate of Return method is a more reasonable approach since a discount factor is not required. The IRR for an investment proposal is the discount factor that equates the present value of the expected cash outlfows with the present value of the expected inflows.

$$\sum_{t=0}^{n} \left[\frac{A_t}{(1+r)^t} = 0\right]$$

The acceptance criterion generally employed with the IRR method is to compare the internal rate of return with a required rate of return known as a cut-off or hurdle rate; the hurdle rate normally being the firm's cost of capital. If the IRR exceeds this rate the project is accepted; if not it is rejected. In considering several projects, that one with the greatest IRR is usually selected. This method like the NPV, however, is essentially corporate oriented and needless to say suffers from the same drawbacks.

A third and final suggested approach is a simple "breakeven" analysis of each level of modularity. In this case the breakeven point may be considered the payback period of the investment; that is the point in time in which the initial cash investment is recovered. In this case it is the number of years required for the life cycle cost savings and the modular derived benefits to offset the increased acquisition cost. The selection criterion would be to select that project which has the shortest payback period. Like the others it has serious drawbacks such as it fails to consider the time value of money and does not consider cash flows after the payback period. In addition it does not take account of the magnitude or timing of cash flows. Finally the problem of mixing apples and oranges exists with this analysis.

5.8 Multi-Attribute Utility Analysis

The previous methods all seemed to suffer from common drawbacks. Therefore what is needed is a design/decision approach which:

1. Is able to work with acquisition cost, savings and benefits without having to convert to common units.
2. Incorporates a design philosophy or design priorities
3. Incorporates the possibility of a changing enemy threat and/or a nonstatic rate of change in the technology.

4. Is not necessarily corporate oriented.
5. Considers the utility of the buyer in investment decisions.

The decision process that best meets the criteria is the combination of multi-attribute utility theory and decision tree analysis. Basic utility theory and decision tree analysis are common and familiar tools presently used by managers in many decision analysis studies. However, multi-attribute utility theory is a fairly new concept and is worth further discussion. Like the single attribute utility theory, the decision maker's utility towards a commodity is assessed through a structured series of lotteries. The commodity need not be solely in units of dollars and in fact such things as reaction time, accuracy, etc. may be the attribute being assessed. Therefore, the multi-attribute theory is exactly as its name implies: the decision maker's utility assessment of more than one attribute at the same time.

For this study a two attribute case shall be selected and the decision maker's utility assessed. The attributes are the two biggest impacts of modularity: increased acquisition cost and increased availability. Obviously an increase in availability is desirable while an increase in acquisition cost is considered undesirable therefore an increasing acquisition cost would have a decreasing utility while an increasing availability would have an

increasing utility. The problem could easily be expanded into a more then two attribute problem because there are more benefits derived from expanded modularity design other than increased availability over the life cycle. Increased R & M, reduced manning skills and reduced design time are as previously mentioned additional benefits and could also be incorporated. However, availability is by far the largest benefit and is the easiest to estimate and measure. The others are much more difficult to estimate and quantify. Therefore, only the utility of trading off acquisition cost anu availability will be analyzed.

It is also assumed that the decision maker for this case is not necessarily a single individual but a combination of those groups in the Navy that are going to purchase the ship and those that are goint to operate it. In addition the decision maker's utility assessment is based on the acquisition of a large class (e.g. more than 50 units) of combatant type vessels which include the frigates, the destroyers and the cruisers. The multi-mission ships such as these show the greatest promise of increased benefits from expanded use of modularity. The electronic and weapons payload systems for these ships are the most sensitive to technology change and show a much higher rate of obsolescence than the payload items on other types of Navy ships. A

Navy tanker or tender would not reap nearly as much benefit from modularity since its payload items are fairly static in nature. That is a significant increase in availability could not reasonably be expected since they do not require frequent and extensive M & C as do the combatants.

5.8.1 Defining the Consequence Space

Appendix A outlines the general procedure for developing the two attribute utility functions that was followed in this study. The first step was to introduce the terminology and items to the decision maker and develop the consequence space. For this decision problem the two scalar attributes consisted of acquisition cost and availability. The range of acquisition cost was based on the outcome of the DX/DXG modularity study by Booz Allen Applied Research[3] the study showed that expanded modularity increased acquisition cost by approximately 5%. Therefore, it was assumed that an austere design that incorperates the basic state of the art in modularity costs $100-million to design and build, the expanded modular deisgn cost $105-million. This may appear at first to be an insignificant spread on the acquisition cost, however, when one considers an acquisition program of 60 ships the additional 5-million per ship is no longer insignificant. The second attribute, availability, ranges from 75% to 95%. These figures are by no means unrealistic, however, the basis of their selection

will be presented later in this chapter. What bears mentioning at this point, however, is that present ship availability is approximately 80-85%. The consequence space that was used follows:

$$1.0 \times 10^8 \leq x \leq 1.05 \times 10^8$$

$$75\% \leq y \leq 95\%$$

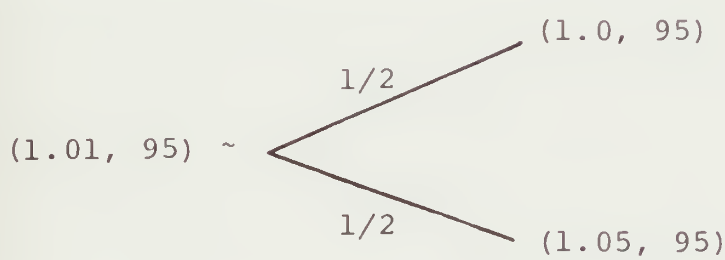
and is illustrated in Figure .

5.8.2 <u>Verifying Utility Independence</u>

Utility independence of each attribute was verified next. This was accomplished by posing several structured lotteries to the decision maker. Because the actual decison makers in the Navy department were not readily available in order to assess their utility on this subject, several of the Navy and Coast Guard students and faculty in the Ocean Engineering Department were asked to put themselves in the position of the actual D/M. Although the simulated results of the utility assessment may not be exactly those of the real life D/M, what is important is the methodology in preforming the analysis and not the results. Finally becuase the design philosophy has a great impact on the entire design process the D/M was asked to keep in mind the DTC philosophy for this utility assessment. After

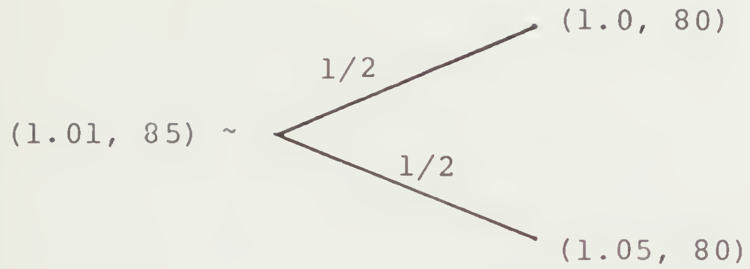
his formulation was completed and analyzed the D/M was asked o switch hats and consider the "Design to Performance" or the Design to Change" philosophy.

To verify whether x was utility independent of y the evels of y was chosen at 95% and the range of x from .0 x 10^8 to 1.05 x 10^8. After posing several lotteries f equal probability of (1.0 x 10^8, 95) and (1.05, 95) the ecision maker converged on a value of (1.01, 95) as being qually desirable to the lottery.

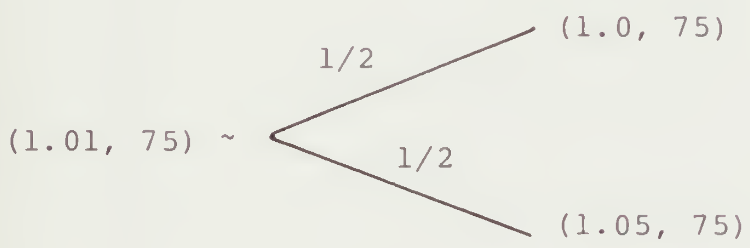


IOTE: Powers have been dropped from acquisition figures.

he concentration was next moved to a new set of consequences vith a different amount of y in common. This level was set at 90% availability. When confronted with similar ype lotteries as before the D/M saw no reason to change is value for x and felt that the level of y should not nfluence his answer. Therefore the consequence of (1.01, 80) was equally desirable to the lottery of (1.0, 80: 1/2; 1.05, 80).



From the above results x appears to be utility independent of y but as one last check a new y level of 75% was selected. Again the D/M converged on 1.01 for x.



Therefore for the D/M x as Figure 24 illustrates that x was utility independent of y.

A similar type of lottery structure was used to determine whether y was U/I of x. To begin with an acquisition cost level of 1.02×10^8 was chosen and an equal probability of 75% or 95% availability. The D/M converged to an availability of 90% as being equally desirable.

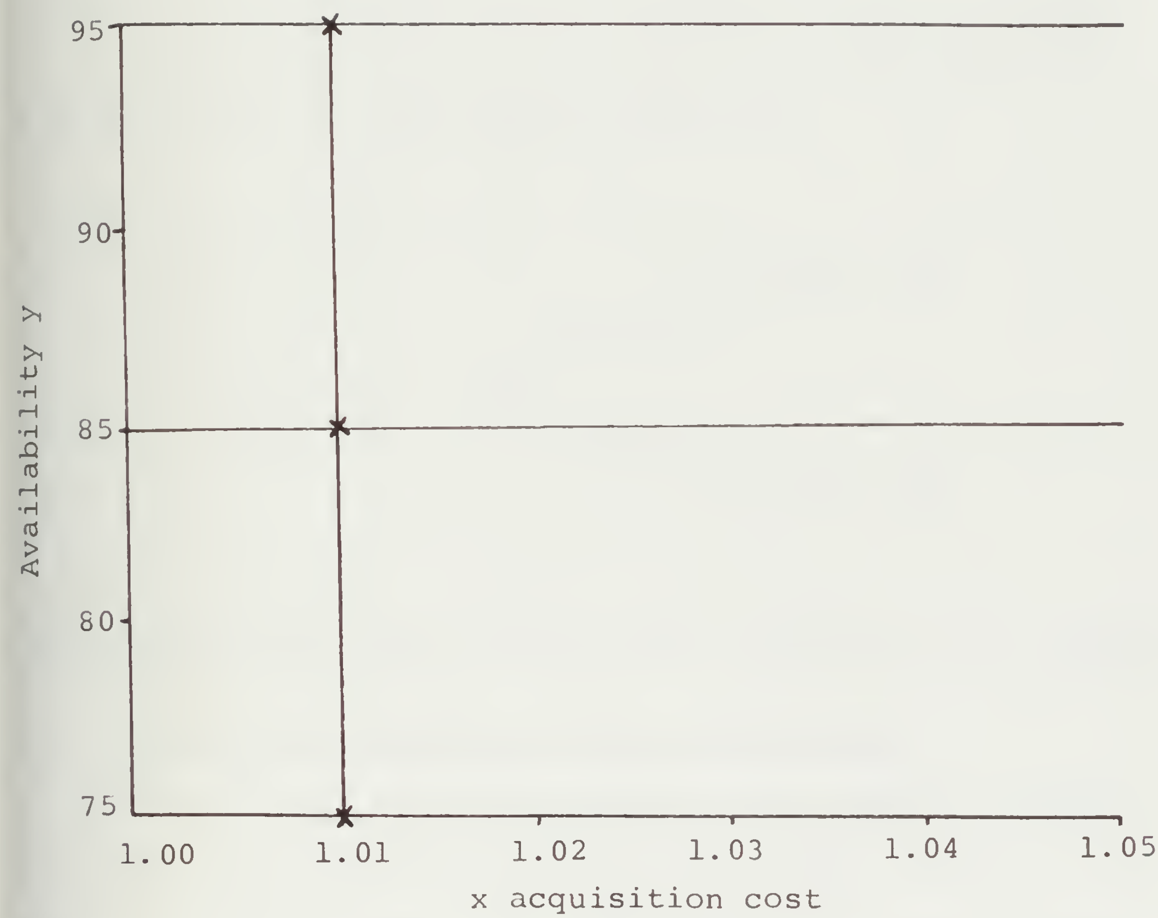
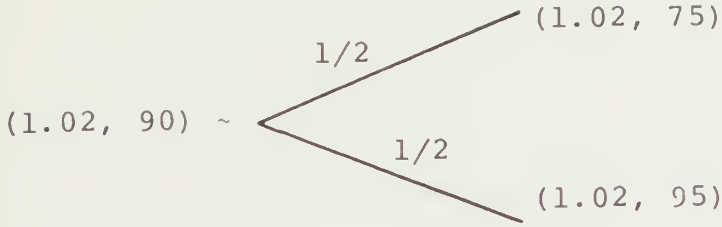
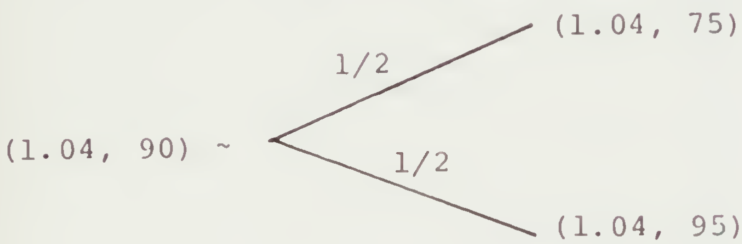


FIGURE 24 Plot: x Utility Independent of y



A new level of x of 1.04 was chosen and again the /M selected 90% as being equally desirable.



t was assumed with these results that y was U/I of x, Figure 25

.8.3 Assessing Conditional Utility Functions

Conditional utility functions were easily assessed nd in fact the procedure was exactly the same as that of one attribute function. For two attributes, one attribute as fixed and the utility of the other was assessed over its ntire range. To begin with, however, the sacle had to be rbitrarily set. For this analysis the following values ere assigned to the utility function extremities:

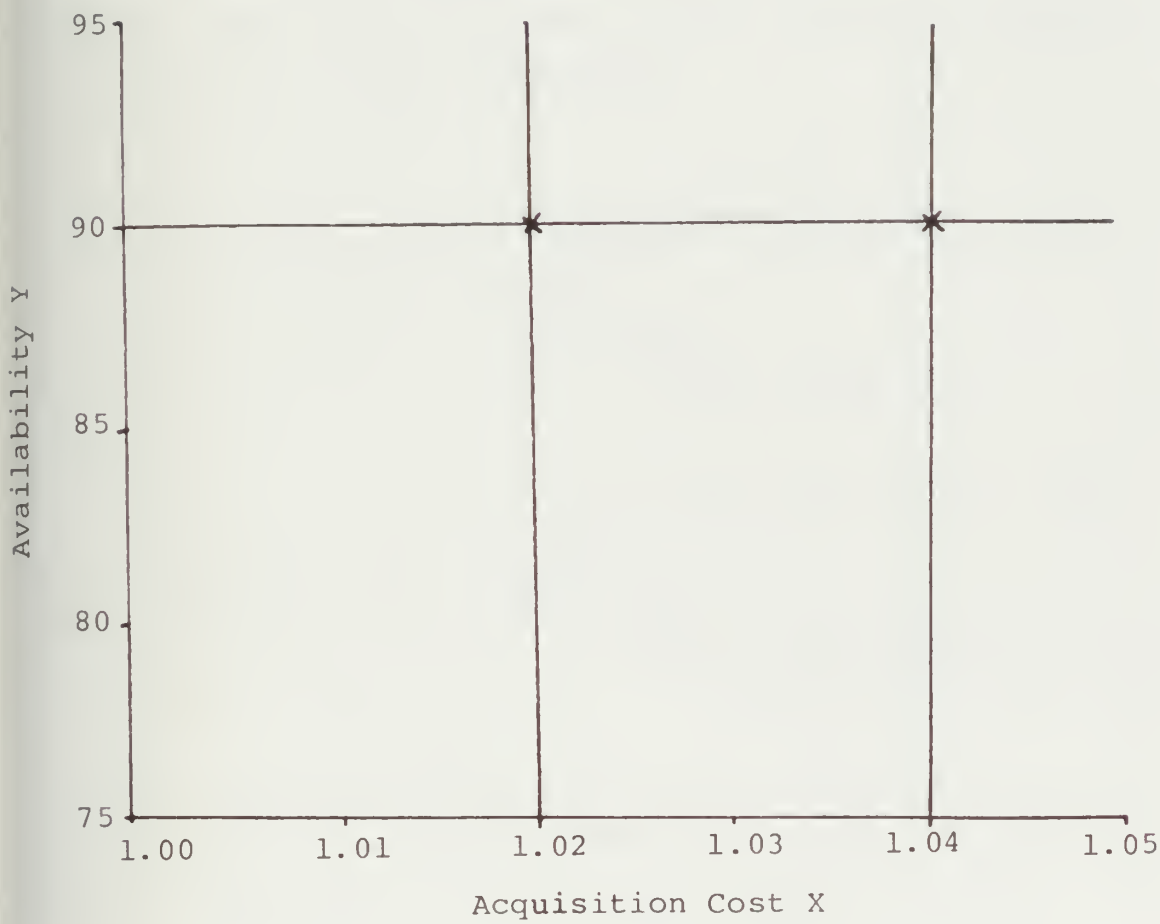


FIGURE 25 Plot: Y Utility Independent of X

$$u_1(1.0,\ 95) = 0.0$$

$$u_1(1.05,\ 95) = -1.0$$

$$u_2(1.0,\ 95) = 0.0$$

$$u_2(1.0,\ 75) = -1.0$$

In deriving the conditional utility function of x, y was set at 95% and the D/M was again posed with a set of lotteries. From the verification of U/I, however, one point on the curve was already established.

$$1.01\ 95 \sim \begin{cases} \xrightarrow{1/2} (1.0,\ 95) \\ \xrightarrow{1/2} (1.05,\ 95) \end{cases}$$

$$u_1(1.01,\ 95) \sim \begin{cases} \xrightarrow{1/2} u_1(1.0,\ 95) = 0.0 \\ \xrightarrow{1/2} u_1(1.05,\ 95) = -\ 1.0 \end{cases}$$

$$\therefore\ u_1(1.01,\ 95) = -\ .5$$

Two other points were equated from the outcomes of the following lotteries:

1)

$$(1.022,\ 95) \sim \begin{cases} \xrightarrow{1/2} (1.01,\ 95) \\ \xrightarrow{1/2} (1.05,\ 95) \end{cases}$$

$$u_1(1.023,\ 95) \sim \begin{cases} \xrightarrow{1/2} u_1(1.01,\ 95) = -\ .5 \\ \xrightarrow{1/2} u_1(1.05,\ 95) = -\ 1.0 \end{cases}$$

$\therefore\ u_1(1.022,\ 95) = -\ .75$

2)

$$(1.005,\ 95) \sim \begin{cases} \xrightarrow{1/2} (1.0,\ 95) \\ \xrightarrow{1/2} (1.01,\ 95) \end{cases}$$

$$u_1(1{,}005,\ 95) \sim \begin{cases} \xrightarrow{1/2} u_1(1.0,\ 95) = 0.0 \\ \xrightarrow{1/2} u_1(1.05,\ 95) = -\ .5 \end{cases}$$

$\therefore\ u_1(1.005,\ 95) = -\ .25$

The conditional utility function for x is depicted in Figure 26.

In a similar fashion the conditional utility function of y was derived with x set at 1.0. Also from the U/I verification the point, $u_2(1.0,\ 90) = -.5$ was already established.

$$(1.0,\ 90) \sim \begin{cases} \xrightarrow{1/2} (1.0,75);\ u_2(1.0,75) = -\ 1.0 \\ \xrightarrow{1/2} (1.0,95);\ u_2(1.0,95) = 0.0 \end{cases}$$

$\therefore\ u_2(1.0,\ 90) = -\ .5$

The two remaining points were also established with lotteries.

1)

$$(1.0,\ 93) \sim \begin{cases} \xrightarrow{1/2} (1.0,90);\ u_2(1.0,90) = -\ .5 \\ \xrightarrow{1/2} (1.0,95);\ u_2(1.0,95) = 0.0 \end{cases}$$

$\therefore\ u_2(1.0,\ 93) = -\ .25$

2)

$$(1.0,\ 86) \sim \begin{cases} \xrightarrow{1/2} (1.0,75);\ u_2(1.0,75) = -\ 1.0 \\ \xrightarrow{1/2} (1.0,90);\ u_2(1.0,90) = -\ .5 \end{cases}$$

$\therefore\ u_2(1.0,\ 86) = -\ .75$

The above points established the conditional utility curve for y, Figure 27. At this point the conditional utility functions appeared to be consistent with what one would expect in the real world situation under the DTC concept.

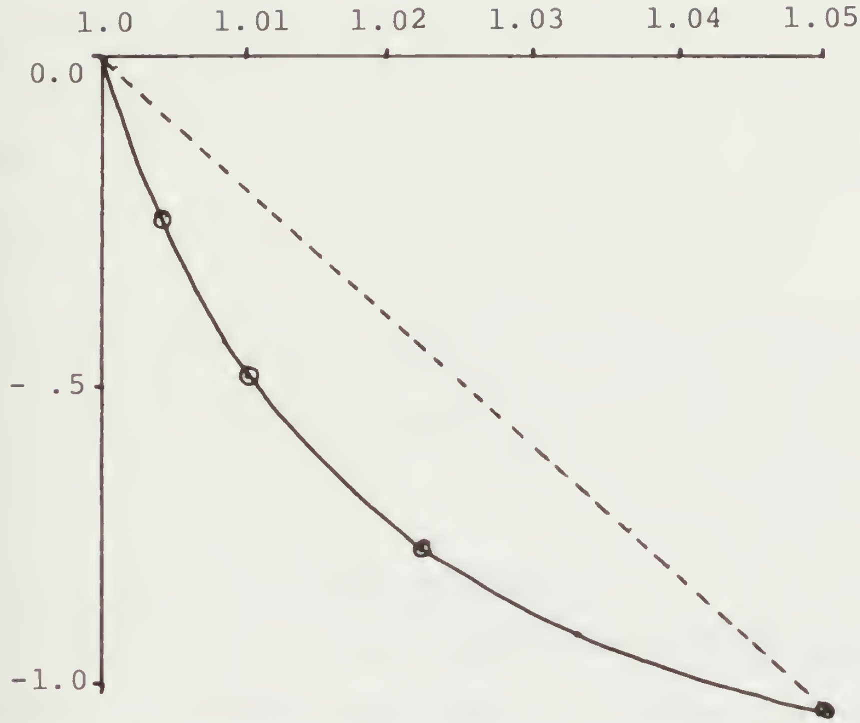


FIGURE 26 Conditional Utility Plot of X; $u_1(x,95)$

FIGURE 27 Conditional Utility Plot of Y; $u_2(1.0,4)$

The curves showed a definite risk proneness; that is the utility of the expected value was less than the expected value of the utility.

$$u(E(\tilde{x})) < E(u(\tilde{x}))$$

The D/M was perhaps likely to gamble a little bit with the acquisition cost in trading off the ship's availability.

5.8.4 <u>Assessing the Scaling Constants</u>

The third step in formulating the utility function was to compute the scaling constants. To begin, the scale wasagain arbitrarily set to the following limits:

I. $u(1.05, 95) = 0.0$

$u(1.05, 75) = -1.0$

II. To the D/M the consequence (1.05, 95) was preferred to the consequence (1.0, 75), however, the consequence (1.05, 95) was equally desirable to (1.0, 80).

$$(1.05, 95) > (1.0, 75)$$

$$(1.05, 95) \sim (1.0, 80)$$

III. Set $u(1.05, 95) = a_1$

$u(1.0, 75) = a_2$

IV. Therefore from the above:

$$u(x,\ 95) = -\ a_1u_1(x,\ 95)$$

$$u(1.0,\ y) = -\ a_2u_2(1.0,\ y)$$

V. By substituting:

$$-a_1u_1(1.05,\ 95) \sim -a_2u_2(1.0,\ 80)$$

VI. From Figures 25 and 26

$$u_2(1.0,\ 80) = -\ .94$$

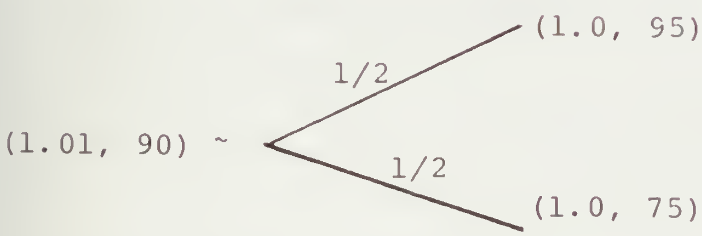
$$u_1(1.05,\ 95) = -\ 1.0$$

$$\therefore\ a_1 = .94\ a_2$$

II. $u(x,y) = -\ a_1u_1(x,95) - a_2u_2(1.0,y) -$

$$\frac{1 - a_1 - a_2}{a_1\ a_2}\ (-a_1u_1(x,\ 95))(-a_2u_2(1.0,y))$$

III. The D/M was presented an final lottery with the following results



$$\therefore\ u(1.01,\ 90) = -\ .5$$

IX. From VII

$$u(1.01,\ 90) = -\ 1/2 = -\ .94\ a_2u_1(1.01,\ 95)-a_2u_2(1.0,90)$$

$$+\ \frac{-1\ -1\ .94\ a_2}{.94\ a_2}\ (-.94\ a_2u_1(1.01,\ 95)(-a_2u_2(1.0,\ 90))$$

X. From Figures 26 and 27

$$u_1(1.01,\ 95) = -\ .48$$

$$u_2(1.0,\ 90) = -\ .53$$

XI. Substituting X into IX

$$a_1 = -\ .475$$

$$a_2 = -\ .505$$

XII. Finally:

$$u(x,y)=.475u_1(x,95)+.505u_2(1.0,y)-.02u_1(x,95)u_2(1.0,y)$$

The three dimensional utility plane is illustrated in Figure 28.

5.9 Decision Tree Formulation

5.9.1 Introduction

The utility function for the modular design under DTC as derived in the last section has very little meaning in the decision analysis unless the utilities are employed in a decision tree analysis in order to determine what level of

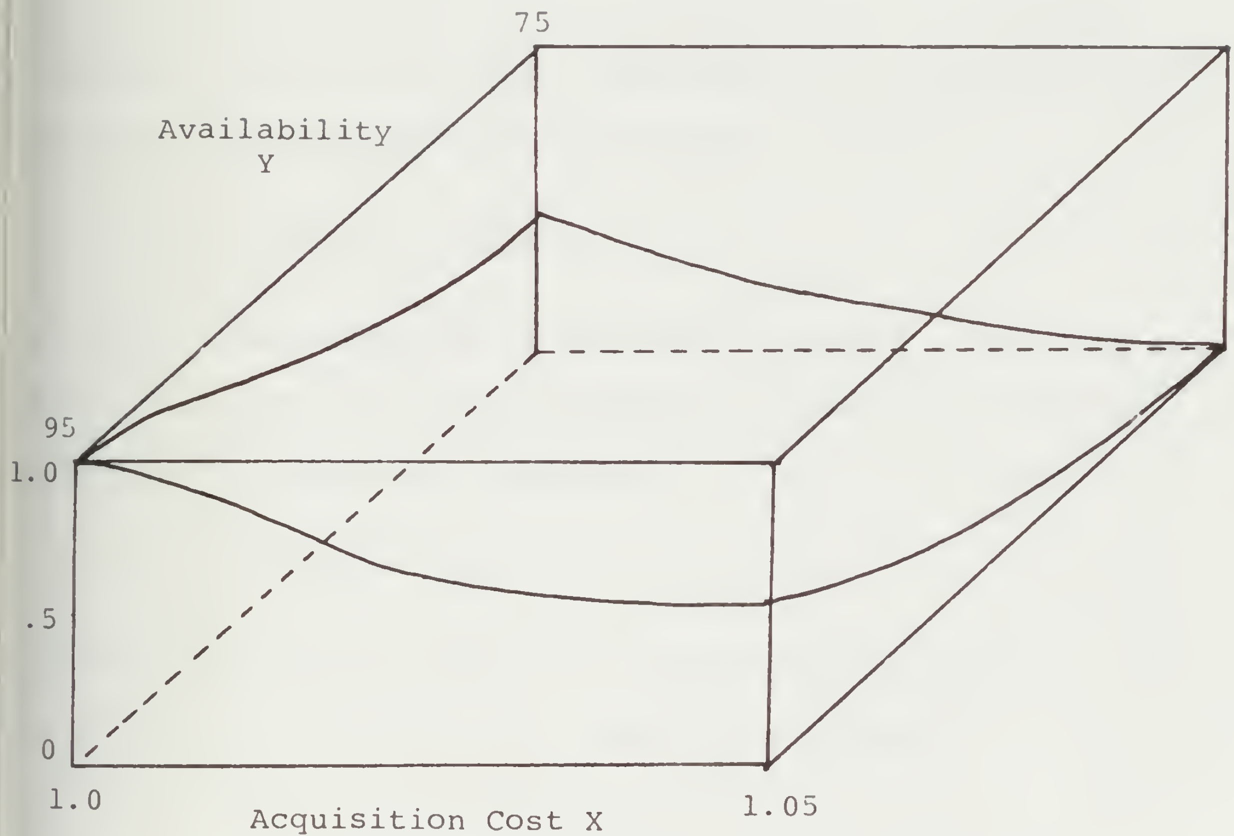


FIGURE 28 Utility Plane; u(x,y)

NOTE: All utilities have been increased by 1.0 in order to move the plane onto the positive utility scale.

modularity is needed. One may ask why not use the actual payoffs or expenses in the decision tree rather than their equivalent utilities. Unfortunately, not everyone is an EMVer; that is, one that selects the *Expected Monetary Value* in all lotteries. In fact, most people exhibit either risk proneness or risk averseness in choosing a utility equivalent for a given lottery. A D/M as defined in the last section, is risk averse if the expected value of a lottery is greater then the certainty equivalent or that consequence that is equally desirable to the lottery. That is:

$$u[E(\tilde{x})] > E[u(\tilde{x})]$$

Of course, risk proneness is the exact opposite. The risk premium is defined as the difference between the expected value and the certainty equivalent.

$$R/P = EV - CE$$

Therefore because the D/M is not always an EMV'er, by expressing the decision tree "payoffs" in terms of utility the D/M's proneness or averseness to risk is captured in the decision tree structure thus giving more meaningful results in choosing the most profitable or least cost course of action.

5.9.2 Assumptions

In order to structure the tree several assumptions were made relative to the impact of modularity on availability and to the number of modernizations and conversions a combatant may undergo during a lifetime. First of all from the results of the Booz Allen Study it was assumed that the highest level of feasible modularity in a ship design reduced M & C time by 50% and ROH time by 25%. In addition no matter how much modularity was employed, all ships had the same life span - 25 years. Finally, it was assumed that, based on the extrapolation of current data, the possibility existed that a combatant may undergo 3 M & C in a 25 year lifetime depending on the rate of technology.

Figures 29, 30 and 31 were derived from the information in Table 1 andformed the basis of the previous assumption. The significant points in these figures are that due to the increased rate of obsolescence the length of time from launch to the first M & C has become shorter and shorter with the newer ships. The duration of the M & C, however, has been greatly reduced due to the increased use of lower level modules in recent years. With the 1052 class having only about 4 years of service before its first M & C it is quite conceivable that this class will have to undergo another M & C before retirement and not totally impossible that two more will be required. Therefore, it was assumed that a new design may require 1, 2 or 3 M & C during a 25 year life span.

TABLE 1

COST BREAKDOWN FOR PAST MODERNIZATION/CONVERSION PROGRAMS

SHIP CLASS	YEAR COMMISSIONED	DURATION OF (M)ODERNIZATION OR (C)ONVERSION	FY74 $ IN MILLIONS			
			AVG. BASIC CONSTRUCTION COST	AVG. GFE COST	AVG. OTHER COST	AVG. TOTAL END COST
1. CLEVELAND (CLG-3)	1945 (launched)	1956-25 mo.(C)	42.4	75.6	19.8	137.8
2. CLG 4&5	1945	1957-40 mo.(C)	48.4	47.7	16.2	112.3
3. CLG-6	1945	1957-35 mo.(C)	47.2	41.3	16.0	104.5
4. CLG 7&8	1944	1957-29 mo.(C)	37.9	36.5	17.3	91.7
5. ALBANY (CLG10-12)	1945/1946	1959-47 mo.(C)	80.1	119.5	21.4	221.0
6. FORREST SHERMAN (DDG31-34)	1956-1959	1965-24 mo.(C)	21.8	21.7	15.4	58.9
7. MITSCHER (DDG35&36)	1953	1966-32 mo.(C)	20.1	22.2	28.1 (Extensive Rehab.)	70.4
8. FORREST SHERMAN (8 ships: DD933, et.al.)	1956-1959	1967-20 mo.(M)	16.1	5.0	12.2 (Extensive Rehab.)	33.3
9. ALBANY (CG10)	1962(as CG)	1967-30 mo.(M)	20.3	26.7	25.3	72.3
10. COONTZ (8 ships: DLG6 et.al.)	1959-1961	1968-16 mo.(M)	20.5	22.9	23.5 (Extensive Rehab.)	66.9
11. LEAHY (DLG16-DLG24)	1962-1964	1967-14 mo.(M)	12.4	19.9	16.0 (Extensive Rehab.)	48.3

TABLE 1 Cost Breakdown for Past Modernization/Conversion Prographs (6)

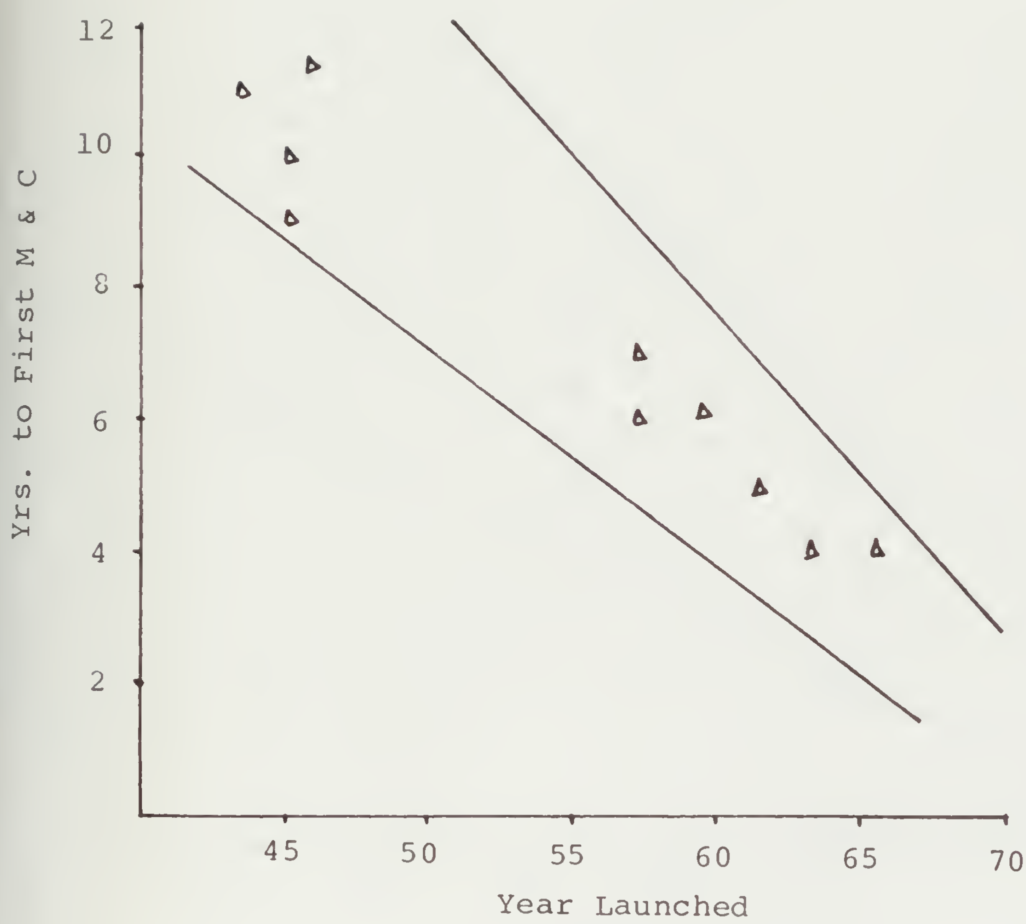


FIGURE 29 Plot: Year Launched vs. Year to First M & C

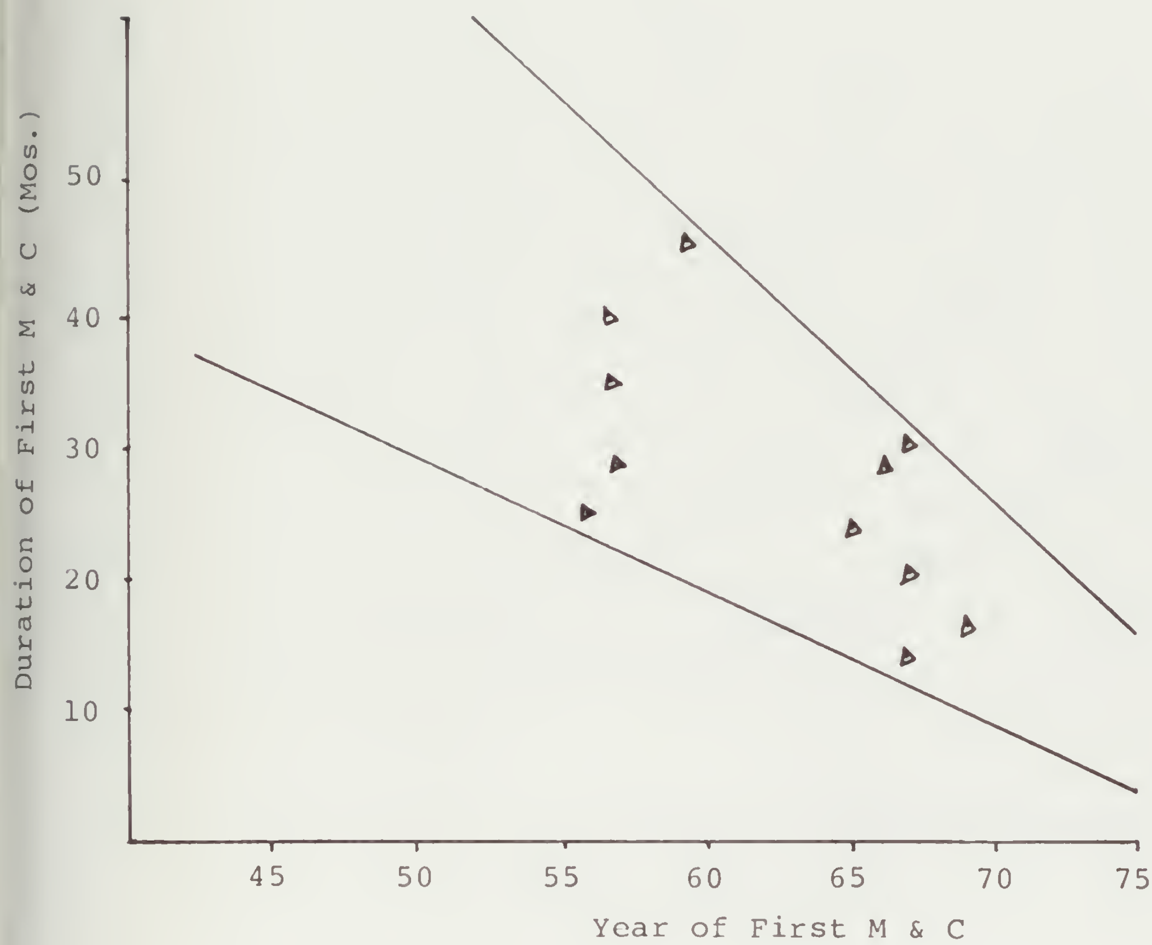


FIGURE 30 Plot: Year of First M & C vs. Duration

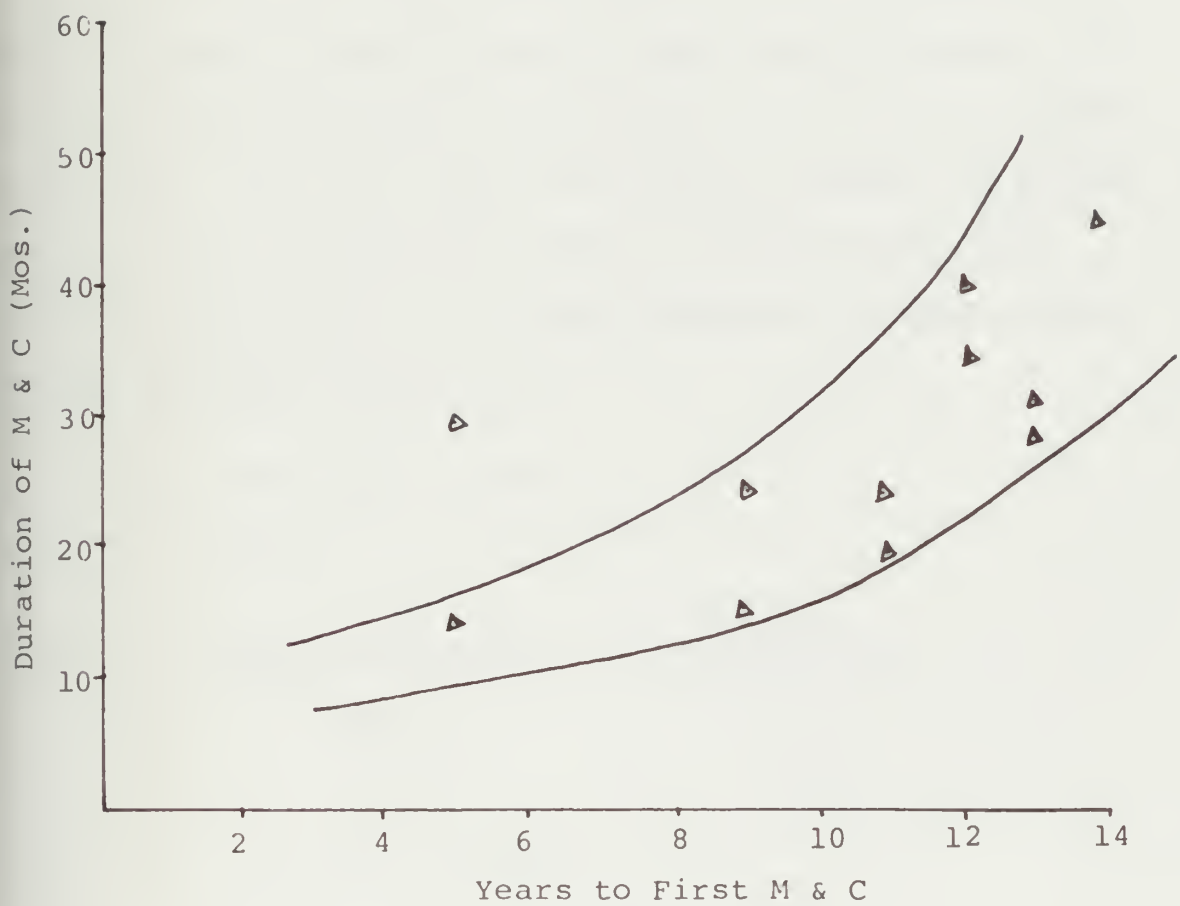


FIGURE 31 Plot: Years to First M & C vs. Duration of M & C

Obviously the percent availability of a combatant depends not only on how many M&C's it undergoes but also how much modularity exists in the design.

In structuring the tree it was initially assumed that there were two different ship designs: one which employed the highest level of modularity feasible and one that only employed the basic state of the art lower level modules. The low level deisgn required 20 months for a M & C and 4 months for each ROH, while the high level design required 10 months for a M & C and 3 months for a ROH. The following table lists the availabilities that were computed for each design based on the above information.

1. 1 M&C per lifetime
   4 ROH

Modularity Level	Availability
High	≈ 95
Low	≈ 85

2. 2 M&C per lifetime
   4 ROH

Modularity Level	Availability
High	≈ 89
Low	≈ 81

3. 3 M&C per lifetime

   3 ROH

Modularity Level	Availability
High	≈ 87%
Low	≈ 75%

5.9.3 Bayesian Approach to Decision Analysis

The assumption in the last section was made that a combatant may undergo 1, 2, or 3 M & C. However obviously not all three have equal probability of occurring. In addition the number required depends on the rate of technology and a measure of this is how soon after launching the ship requires its first M & C. Obviously if a ship undergoes a M & C within 4 years after launching then a high probability exists that an additional M & C will be required before retirement. Conversely if a ship undergoes its first M & C 10-12 years after launching then a high probability exists that it will not require an additional M & C before retirement.

To formulate the tree using a Bayesion approach 3 states of nature were selected as 1, 2, or 3 M & C per ship per lifetime. The three outcomes were:

1. A ship receives its first M&C 3-6 yrs. after launching
2. A ship receives its first M&C 7-9 yrs. after launching
3. A ship receives its first M&C 10-12 yrs. after launching

Finally the author made estimates of the probabilities of the ship requiring 1, 2, or 3 M & C in a lifetime.

P(1 M&C/25 years) = P(I) = .3

P(2 M&C/25 years) = P(II) = .5

P(3 M&C/25 years) = P(III) = .2

In addition the author estimated the following conditional probabilities.

P(I/ship receives first M&C within 3-6 years) = P(I/1) = .7

P(I/ship receives first M&C within 7-9 years) = P(I/2) = .2

P(I/ship receives first M&C within 10-12 years) = P(I/3) = .1

P(II/1) = .2 P(III/1) = .1

P(II/2) = .6 P(III/2) = .2

P(II/3) = .2 P(III/3) = .70

One point needs to be brought out on these probabilities and that is they are not guaranteed to be accurate and in fact may be way out of line. The probabilities are more or less best guesses based on the authors knowledge of this topic. However, the important thing is not the data generated nor the results but the way the data is used to obtain the results in the methodology.

The following conditional probabilities were obtained through Bayes Theorem and the above probabilities.

$$P(I) = P(1)P(I/1) + P(2)P(I/2) + P(3)P(I/3)$$

$$= .3 \times .7 + .5 \times .2 + .2 \times .1$$

$$= .33$$

$$P(II) = P(1)P(II/1) + P(2)P(II/2) + P(3)P(II/3)$$

$$= .3 \times .2 + .5 \times .6 + .2 \times .2$$

$$= .4$$

$$P(III) = P(1)P(III/1) + P(2)P(III/2) + P(3)(III/3)$$

$$= .3 \times .1 + .5 \times .2 + .2 \times .7$$

$$= .27$$

$$P(1/I) = \frac{P(1)P(I/1)}{P(I)} = \frac{(.3)\ (.7)}{.33} = .636$$

$$P(2/I) = \frac{P(2)P(I/2)}{P(I)} = \frac{(.5)\ (.2)}{.33} = .3$$

$$P(3/I) = \frac{P(3)P(I/3)}{P(I)} = .064$$

In order to structure a meaningful decision tree the D/M needs more than just two levels of modularity to choose from. That is, the methodology would not be very helpful if the high level modular design and the low level design were the only ones of interest to the D/M. The D/M is more than likely interested in designing to a level of modularity which is somewhere in between the high and low level designs. He probably does not want to pay the additional acquisition cost of the high level design nor

does he need all the added availability. On the other hand, the low level design may not offer enough flexibility in order to accomplish quick and efficient M & C.

Therefore for this decision problem two intermediate modular levels were added to the high and low level designs. It was assumed that the modular levels differed mainly in the extent to which modularity was incorporated; that is the number of payload subsystems and components modularized and the number of P-1, P-2, P-3, and P-4 modules incorporated. It was further assumed that the increase in acquisition costs of these two intermediate levels in addition to the increased availability described a linear function in relation to the high and low level, Figure 32.

From the above assumptions a consequence chart was drawn up for each level of modularity and for 1, 2 or 3 M & C per lifetime. These consequences were then converted into their corresponding utilities using the previously developed DTC utility function for modular design, Table 3. Finally after all the necessary probabilities and utilities were computed the actual decision tree was drawn up and analyzed, Figures 33a & 33b.

Several points should be brought on the decision tree. First of all there is an upper and a lower branch. The tree starts off with the decision of building one

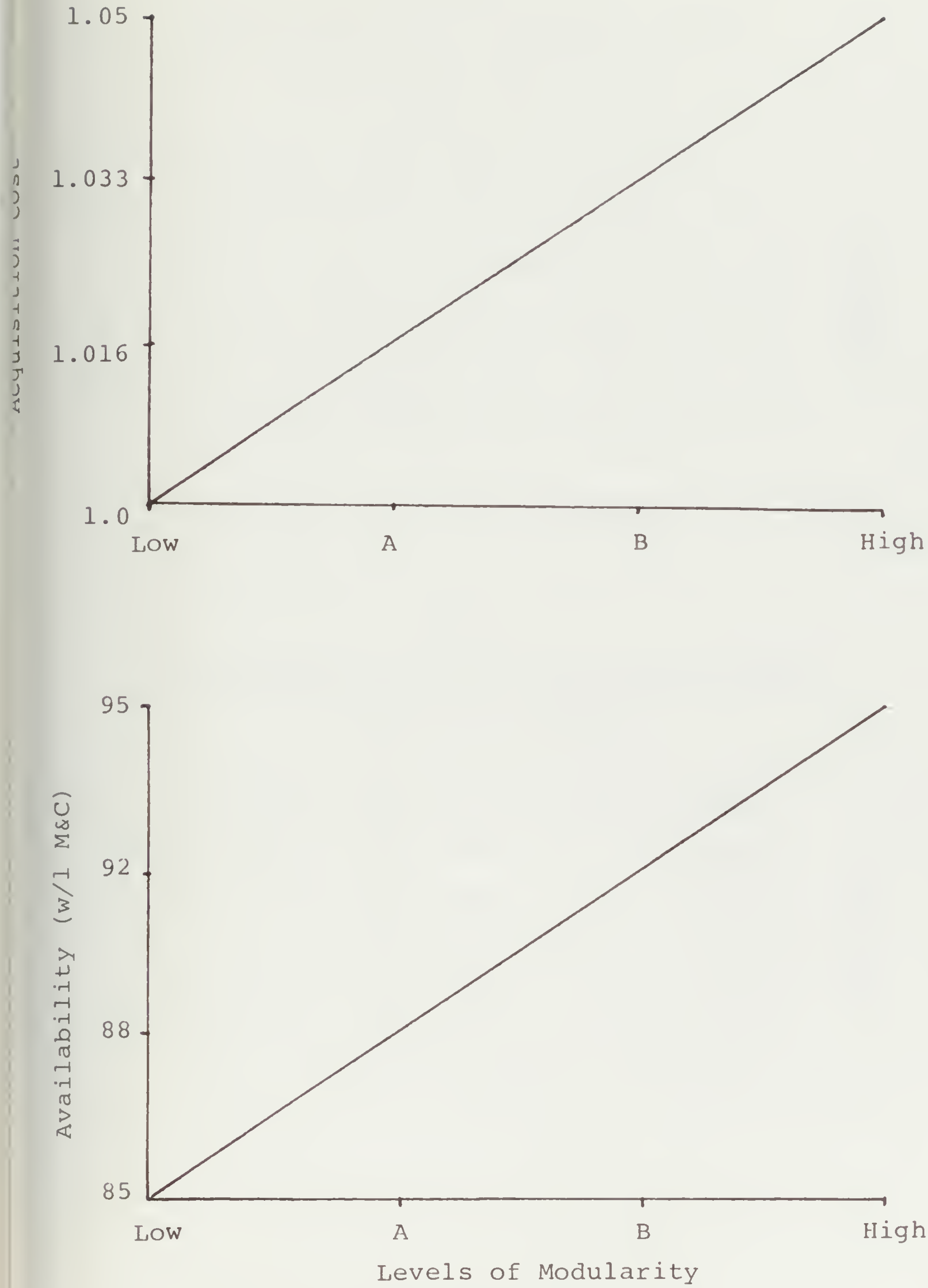


FIGURE 32 Approximations of Levels of Modularity vs. Acquisition Cost and Availability

TABLE 2

Consequence Chart of Modular Levels

No. of M&C Per Lifetime

Level of Modularity	1	2	3
High	1.05, 95	1.05, 89	1.05, 88
B	1.033, 92	1.033, 86	1.033, 83
A	1.016, 88	1.016, 83	1.016, 79
Low	1.0, 85	1.0, 81	1.0, 75

TABLE 3

Consequence Utilities for Modular Levels

No. M&C Per Lifetime

Level of Modularity	1	2	3
High	.525	.236	.194
B	.337	.185	.133
A	.375	.261	.21
Low	.606	.517	.495

of the four modular designs (high, B, A, or low) on the upper branch or gathering additional information and following the lower branch. The upper branch basically looks at the four modular levels and their utility outcomes for each of the possible number of M & C per lifetime. The lower branch is the second option available to the decision maker. Here the D/M may elect to gather additional information such as the approximate obsolescence rate, rate of technology, and/or the level of enemy threat. With this information the D/M can perhaps make reasonable estimates of how soon after commisioning, a combatant requires its first M & C. The lower branch considers three possible outcomes:

1. A ship requires its 1st M&C within 3-6 yrs.
2. A ship requires its 1st M&C within 7-9 yrs.
3. A ship requires its 1st M&C within 10-12 yrs.

Each of these outcomes is followed by the same decision that exists in the upper branch, however, the additional information has somewhat altered the probabilities of occurance for the three states of nature (1, 2, or 3 M&C).

By averaging out and folding back in the normal form of analysis the best strategy for the D/M turned out to be the lower branch (e.g. gathering additional information). The selection criteria for this strategy was based on the fact that a higher utility was attained in the lower

NOTE: Figures in parenthesis are probabilities.

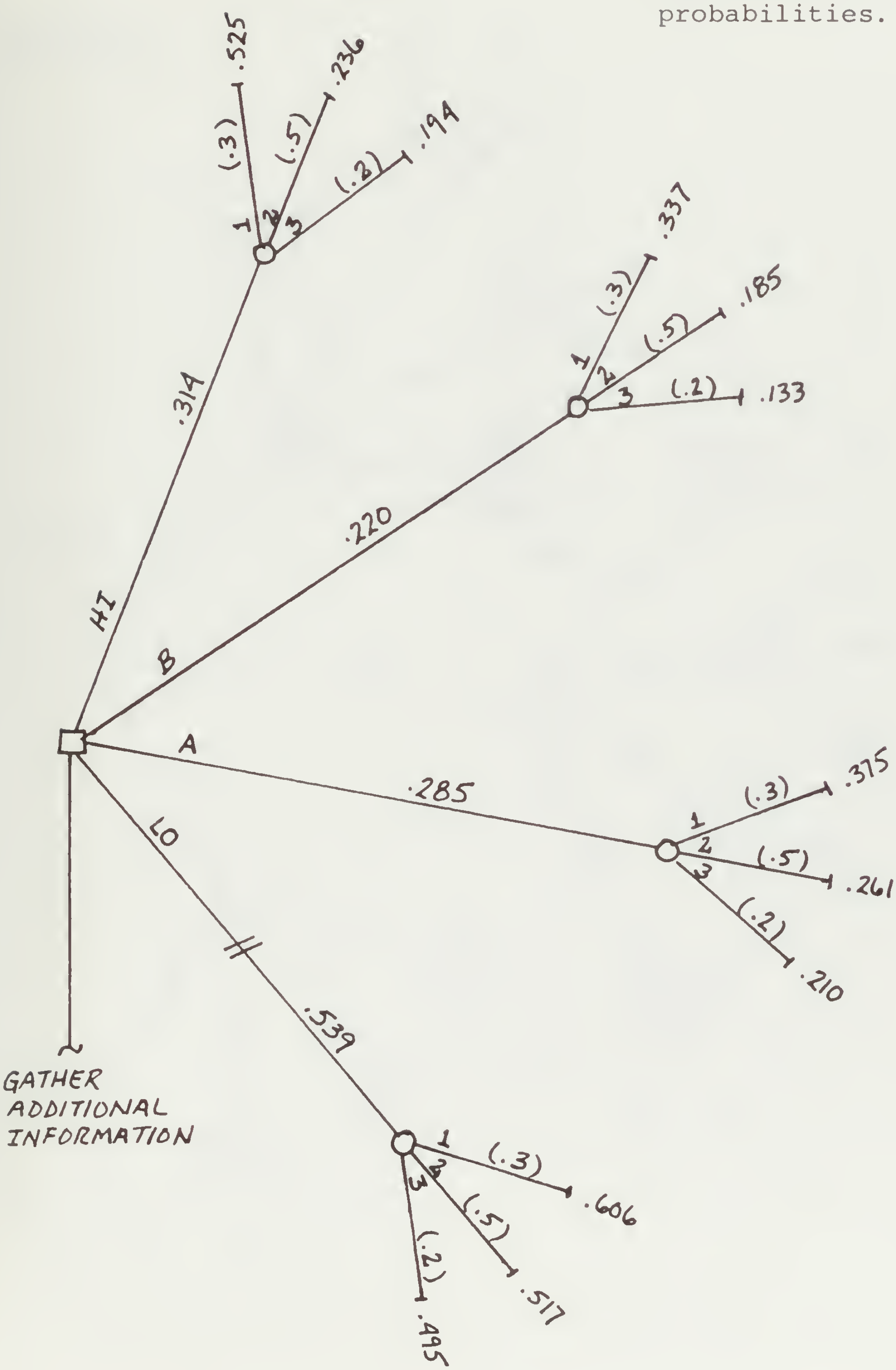


FIGURE 33a Upper Branch of "DTC" Decision Tree

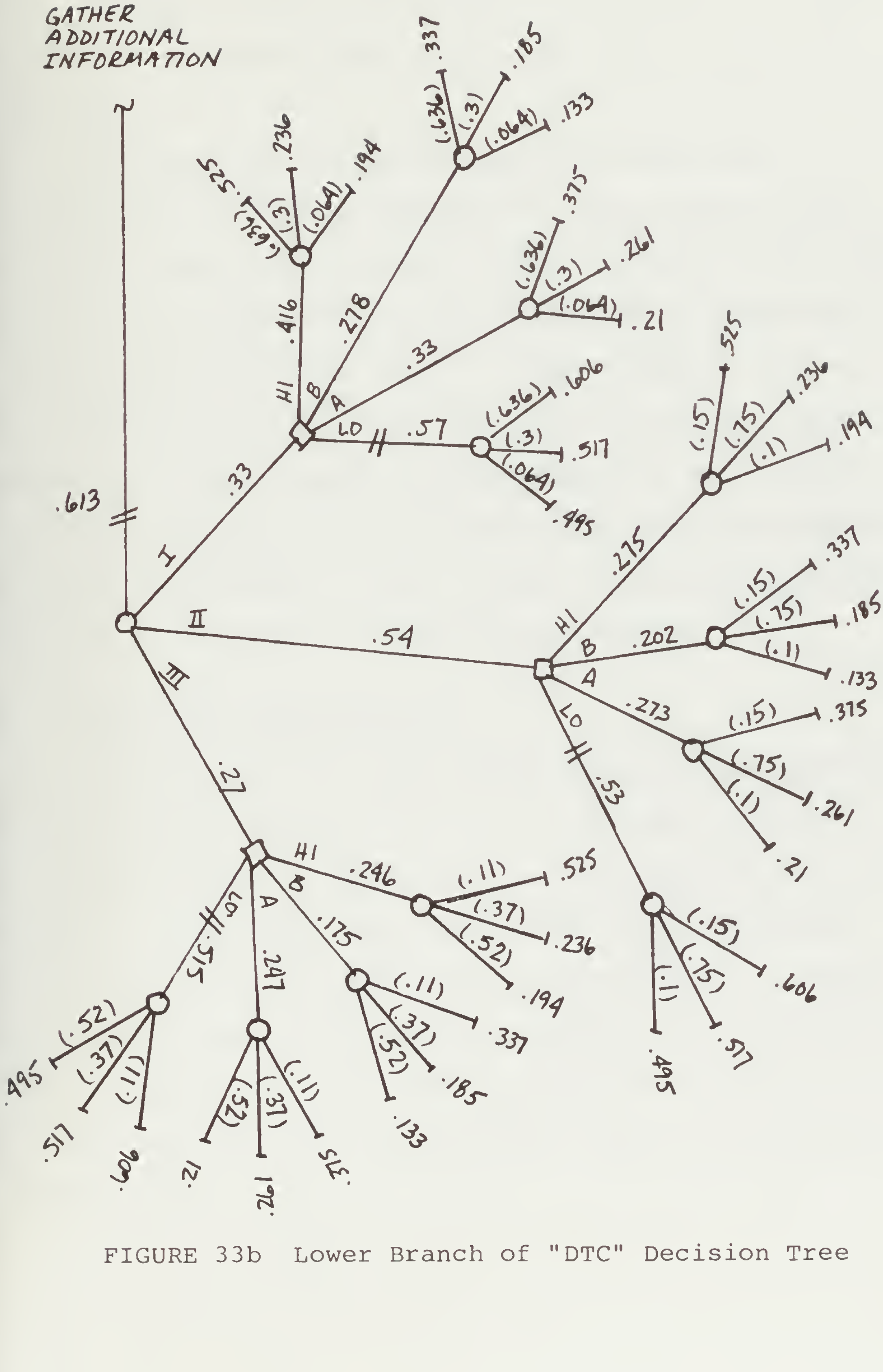


FIGURE 33b Lower Branch of "DTC" Decision Tree

branch. However, it was interesting to note that the highest utility attained in the upper branch was with the low level modular design.

Obviously one can not reasonably assume that a study to gather additional information in the lower branch would be cost free. Therefore, the most one should be willing to pay for this study would be the difference in the upper and lower branch utilities (.613 - .539). However, this figure probably has very little use to the D/M since the conversion of utility back to a consequence of acquisition dollars and availability is difficult because the possibility of multiple roots exists. Also a cost in units of acquisition dollars and availability is perhaps meaningless.

5.10 Extensive Analysis Form

Because the risk prone nature under the DTC philosophy drove the decision maker to select the low level design under all the states of nature an extensive analysis was performed to investigate the sensitivity of this strategy to the probabilities of requiring one or more M & C. However, because four acts and three states of nature were unmanageable for this analysis the problem was condensed to a two act, two state of nature problem. The components used in the analysis are listed below:

State of Nature	---	1 or 2 M&C per lifetime
Experiments	---	gather additional information
Outcomes	---	ship requires its first M&C within 0-6 years of commisioning or 7-12 years
Acts	---	build low level modular ship @ $\$1.0 \times 10^9$/ship or high level modular ship @ $\$1.05 \times 10^9$/ship

In addition the author estimated the following probabilities:

1. There is a 60% chance of a ship requiring 2 M&C and a 40% chance of only requiring one.
2. Given that a ship requires only one M&C in a lifetime the probability it occurs within 0-6 years of commisioning is .3 (i.e $P(I/1) = .3$ and $P(II/1) = .7$ also:
   $P(I/2) = .7$ $\quad\quad$ $P(II/2) = .3$
3. $P(I) = P(1)P(I/1) + P(2)P(I/2)$
   $= .4(.3) + .6(.7)$
   $= .54$

$$P(II) = P(1)P(II/1) + P(2)P(II/2)$$

$$= .4(.7) + (.6)(.3)$$

$$= .46$$

4. $$P(1/I) = \frac{P(1)P(I/1)}{P(I)}$$

$$= \frac{(.4)\ (.3)}{.54}$$

$$= .22$$

$$\therefore P(2/I) = .78$$

$$P(1/II) = \frac{P(1)P(II/1)}{P(II)}$$

$$= \frac{(.4)\ (.7)}{.46}$$

$$= .61$$

$$\therefore P(2/II) = .39$$

Using the same consequence and utilities for the high and low level design as in the normal analysis, the decision tree was set up in Figure 34 and the analysis performed in Table 4 . From the far right column (EMV) it was obvious that the D/M had two different strategies yielding the highest and equal utilities. That is the D/M could either build the low level design or gather additional information but again build the low level no matter what the outcome.

As brought out in the normal form analysis one could not reasonably assume that the process of gathering

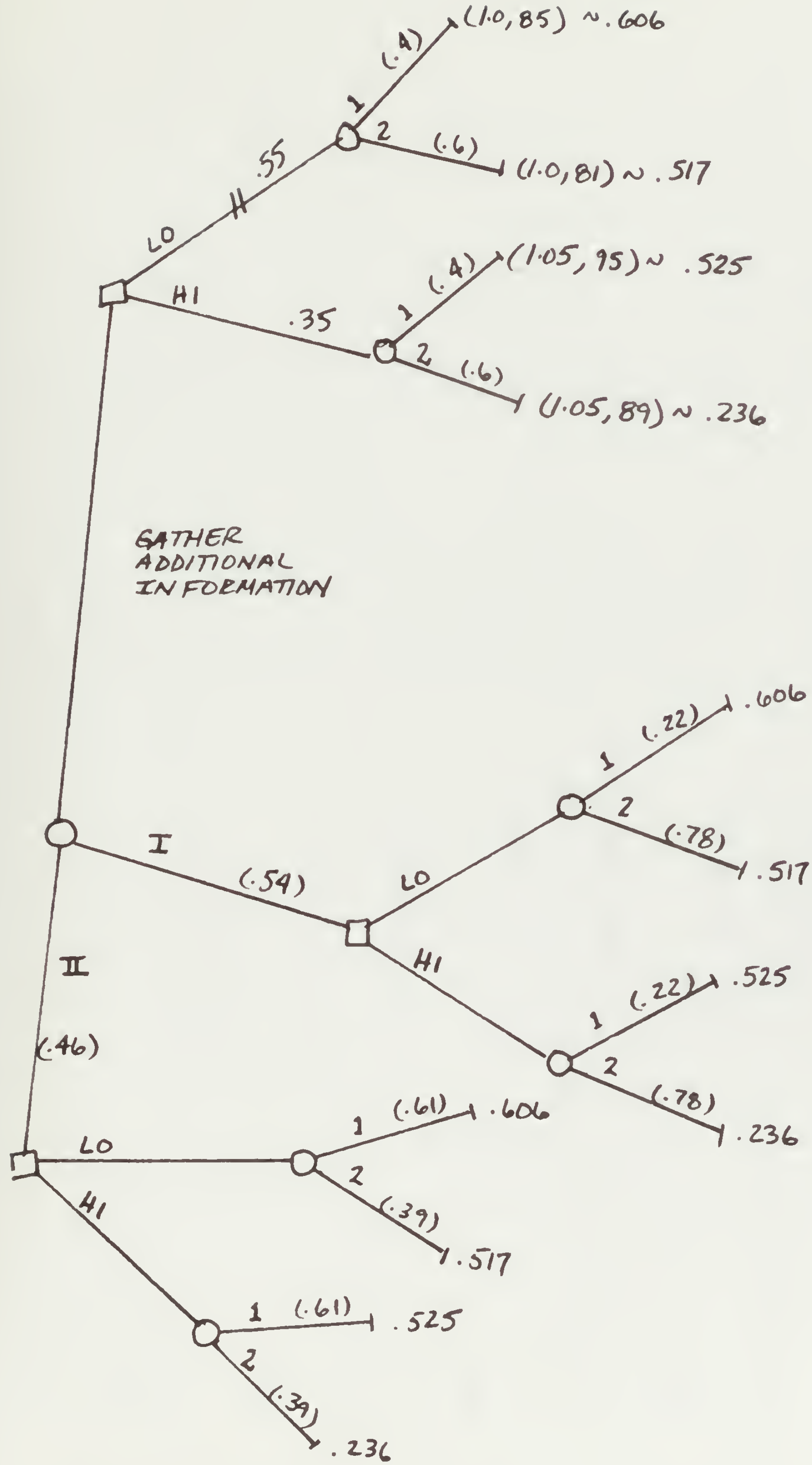


FIGURE 34 Extensive Analysis Decision Tree Without Test Cost

TABLE 4 Extensive Analysis without a Test Cost

Note: figures in parenthesis are probabilities

Strategy	Decision	1 (.4)	2 (.6)	EMV
Build Low Level		.606	.517	.55
Build High Level		.525	.236	.35
	If I Build Low	.606 (.3)	.517 (.7)	
Test		.55	.43	.478
	If II Build High	.525 (.7)	.236 (.3)	
	If I Build Low	.525 (.3)	.236 (.7)	
Test		.58	.32	.424
	If II Build High	.606 (.7)	.517 (.3)	
	If I Build Low	.606 (.3)	.517 (.7)	
Test		.606	.517	.55
	If II Build High	.606 (.7)	.517 (.3)	
	If I Build Low	.525 (.3)	.236 (.7)	
Test		.525	.236	.35
	If II Build High	.525 (.7)	.236 (.3)	

additional information is cost free. Therefore inorder to make the analysis more realistic it was assumed the study increased the ship acquisition cost by an additional $.25 \times 10^6$ dollars. This, of course, changed the utilities for each design for each state of nature. The new utilities are listed below:

$$\left.\begin{array}{l} u(1.0025, 85) = .52 \\ u(1.0025, 81) = .45 \end{array}\right\} \text{Low Level Modularity}$$

$$\left.\begin{array}{l} u(1.0525, 95) = .47 \\ u(1.0525, 89) = .2 \end{array}\right\} \text{High Level Modularity}$$

Because the scale for acquisition cost only went up to 1.05 the utilities for the high level design had to be estimatedwhich was based upon the utility change for the low level design. The new decision tree was constructed, (Figure 35) and the analyses performed in Table 5 . Again building the low level design proved to have the highest utility and therefore proved to be the best strategy.

The meat of this analysis, however, consisted of investigating the impacts of the probabilities of the states of nature (1 or 2 M&C) on the optimal strategy. What the D/M wanted to know was if the probability of 2 M&C per lifetime greatly increased or even decreased would strategy 1, that is build the low level design, still be optimal.

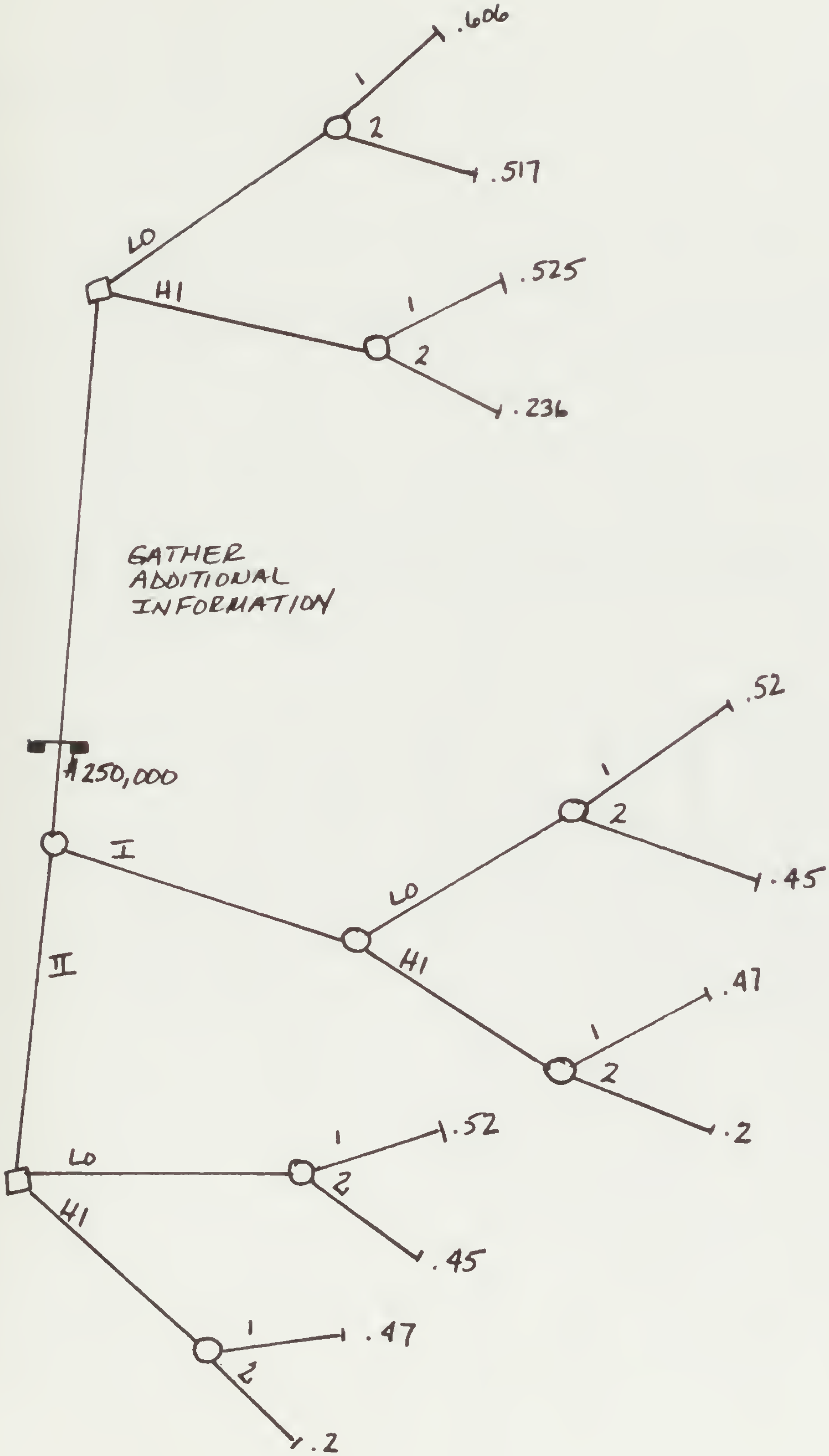


FIGURE 35 Extensive Analysis Decision Tree With Test Cost

Strategy	Decision	1 (.4)	2 (.6)	EMV
1. Build Baseline*		.606	.517	.55
2. Build Modular		.525	.236	.35
	If I Build Base.	.52 (.3)	.45 (.7)	
3. Test		.485	.375	.419
	If II Build Mod.	.47 (.7)	.2 (.3)	
	If I Build Mod.	.47 (.3)	.2 (.7)	
4. Test		.505	.275	.367
	If II Build Base.	.52 (.7)	.45 (.3)	
	If I Build Mod.	.47 (.3)	.2 (.7)	
5. Test		.47	.2	.308
	If II Build Mod.	.47 (.7)	.2 (.3)	
	If I Build Base.	.52 (.3)	.45 (.7)	
6. Test		.52	.45	.478
	If II Build Base.	.52 (.7)	.45 (.3)	

*Optimal Strategy

NOTE: figures in parenthesis are probabilities.

In order to do so the following equations were developed from columns 3 and 4 in Table 5 and plotted in Figure .

P = probability of 1 M&C

1-P = probability of 2 M&C

1. P(.606) + (1-P)(.517) = .517 + .089P

2. P(.525) + (1-P)(.236) = .236 + . 289P

3. P(.485) + (1-P)(.375) = .375 + .11P

4. P(.505) + (1-P)(.275) = .275 + .23P

5. P(.47) + (1-P)(.2) = .2 + .27P

6. P(.52) + (1-P)(.45) = .45 + .07P

It was obvious from the sensitivity plot that the optimal strategy (e.g. strategy 1 - build low level) remained optional throughout the range of P from 0 to 1.0. The fact that strategy 1 remained optimal was perhaps caused by the high risk proneness of the D/M and the utility function. As a comparison to the results of the decision analysis under the DTC philosophy towards modular ship design a similar analysis was also performed under a more risk averse atmosphere that would perhaps exist in a Design to Change or a performance oriented philosophy. The results of the analysis are presented in Appendix B.

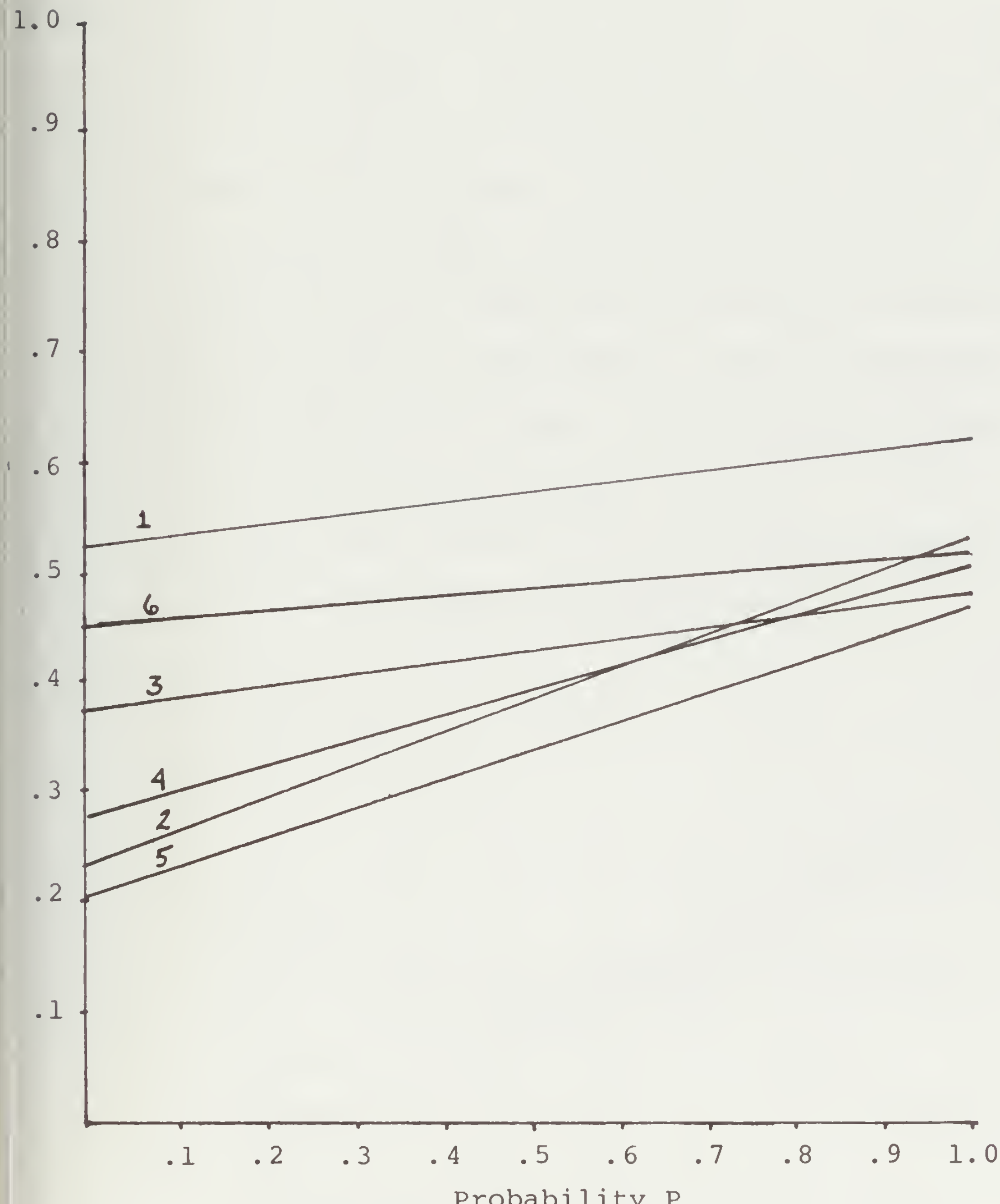
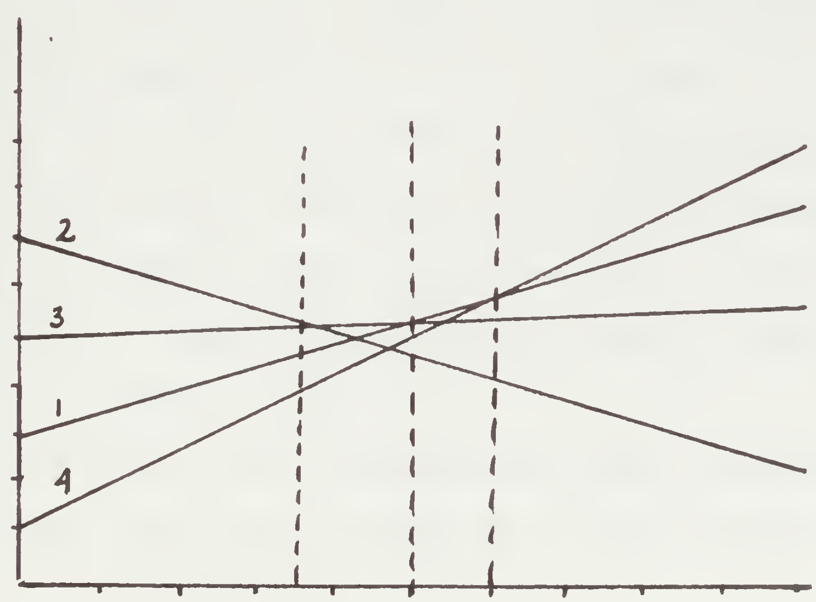


FIGURE 36 Strategy Plot

Some may argue that the subjective probabilities assigned to one and two M&C may be completely out in left field or perhaps that the probability of two M&C is zero because the Navy would never send a ship into a second M&C due to the great expense. Whether this is true or not the obsolescence rate goes on the same regardless and data shows that the point of obsolescence (e.g. point at which the 1st M&C is required) occurs earlier and earlier in the ship's life with each new ship. Therefore the extensive analysis of the decision process is designed to outline different strategies for the ship designer. For the above analysis the designer had a fairly easy strategy. However, in other situations he may have several or all strategies become optimal over a finite range of probabilities.



For instance in the above illustration four strategies are optimal at different ranges of probabilities for 1 M&C.

Strategy	Optimality Range
1	$.6 \leq P < .7$
2	$0 \leq P < .45$
3	$.45 \leq P < .6$
4	$.6 \leq P \leq 1.0$

5.11 Conclusions

The ship design is an extremely difficult, lengthy and expensive process and with the trends of increased enemy threat, reduced acquisition funds, high obsolescence rates and shifting deisgn philosophies the process does not appear to be getting easier. The expanded use of modularity appears to be a viable solution to these problems, however, to date little has been done in terms of actual hardware incorporation, and concrete cost benefit analysis. In addition the designer must decide how much modularity is needed. Obviously an approach that considers the marginal returns of the life cycle benefits and acquisition cost for various modules or levels of modularity in the ship design would be most beneficial to the designer.

In formulating such a methodology some cost benefit study results were utilized in addition to making some basic

assumptions that may be grossly inaccurate. However, the means and not the results is the compatant thing. Certainly some additional research in the areas of these assumptions should make the multi-attribute decision tree analysis a stronger tool. One major drawback, however, as previously mentioned, is the problem of multiple decision makers in the design process. Analyzing many different utilities and reducing them into a single function is not an easy task. Any problem formulation, however, must begin with some groundwork and basic assumptions and the ones in the methodology do not appear to be unmanageable.

Although still in its early stages, the approach of multi-attribute utility to the problem of analyzing the cost and benefits over a ships life cycle for various modular levels appears to be a helpful tool for the ship designer.

APPENDIX A

The process of properly assessing multi-attribute utility functions requires some foresight and improvisation, however, as in the unidimensional, one attribute case the assessment procedure can be segamented for discussion purposes to highlight various aspects which must be completed. Although this thesis focuses on the two attribute utility function the procedure below applies to a multi-attribute utility assessment. A quick summary of a procedure in determing the utility function one might use is

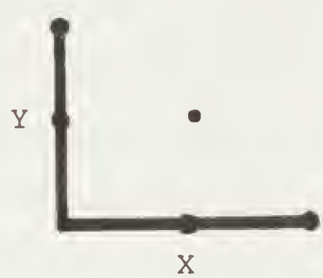
1. Introduce the terminology and ideas.
2. Identify relevent independence assumptions.
3. Assess conditional utility functions.
4. Assess the scaling constant.
5. Check for consistency and iterate.

I. INTRODUCTION

The first step more or less introduces the concept of utility to the decision maker and familiarizes him with the framework that is used in the assessment procedure so that the decision maker and the person assessing are talking the same language. The decision maker must also have explained to him the concept of decision analysis so that he realizes the purpose in assessing his preferences and is sufficiently motivated to think hard about his

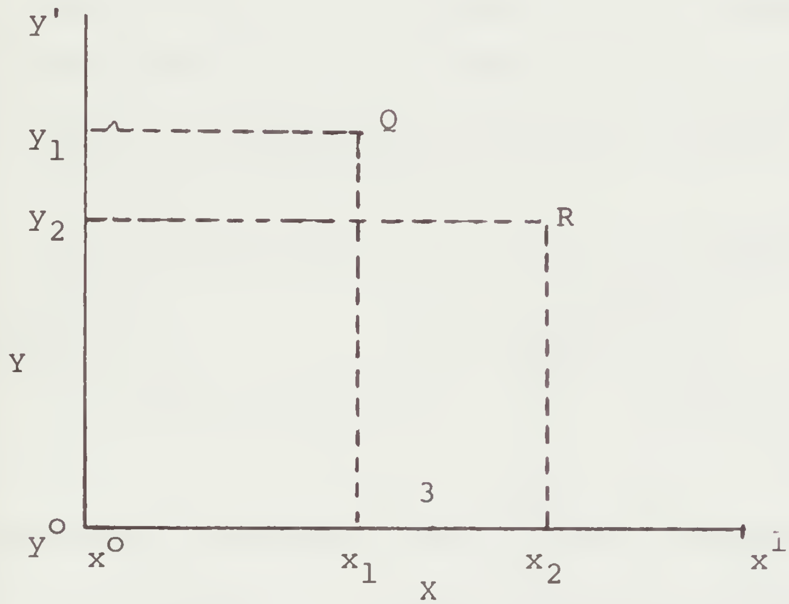
feelings for the various consequences. If this is not accomplished before proceeding then confusion is likely on the part of the decision maker which will lead to non-consistent and meaningless results. It is then necessary to verify any of the additive independence, utility independence, parametric dependence assumptions followed by step 3 which asseses the individual conditional utility functions. The functions are then scaled to a common origin and unit of measure for the overall utility function u(x,y). Finally the consistency of the function is checked by further questioning the decision maker about his preferences and then comparing these to the implications of u(x,y). If inconsistency results then iteration is necessary.

The decision problem is then structured and two scale attributes are chosen (x & y) to describe the consequence space and then to assess a utility function over all possible (x,y). A consequence space to aid the decision maker should be drawn up similar to the one below



It should be made clear to the decision maker that the preferences are his, that there are no objectively correct ones and they represent the subjective feelings of the decision maker.

The decision maker must understand the consequence space below



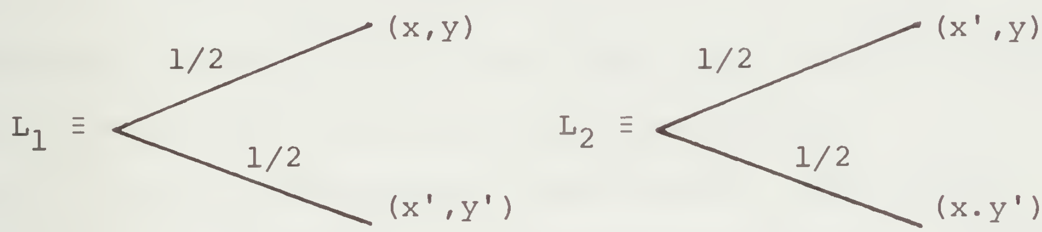
and that consequence Q is $x = x_1$ and $y = y_1$ and R is $x = x_2$, $y = y_2$. He should also realize the directions in which x & y increase.

The next step is to limit the region over which the preferences are assessed to as little a region as possible; that is the maximum and minimum amounts which both x & y can assume. The preferences that will eventually be assessed must only be those for consequences (x,y) $x^o \leq x \leq x'$ and $y^o \leq y \leq y'$ as depicted in the above

figure. As a final check on the D/M's understanding of the consequence space one may, ask him if he prefers consequence T to S. If this agrees with the expected results then the next segment may be pursued.

II. <u>Verification of Independence Assumptions</u>
<u>Additive Independence</u>

The preferences to be assessed are contained in the consequence space $x^o \leq y \leq x'$ and $y^o \leq y \leq y'$ and x and y are additive independent if and only if the lotteries



are indifferent for all amount of x,y given a specific x',y'. The obvious method to verify additive independence is to select a x', and y' and to see if indifference between lotteries L_1 and L_2 hold for some pair of (x,y).

An alternative method for verifying additive independence involves first of all determining mutual independence. However, mutual utility independence is a necessary but not sufficient condition for additive independence. If x and y are mutually utility independent,

they are additive independent if there exists a x_1, x_2, y_1 and y_2 such that

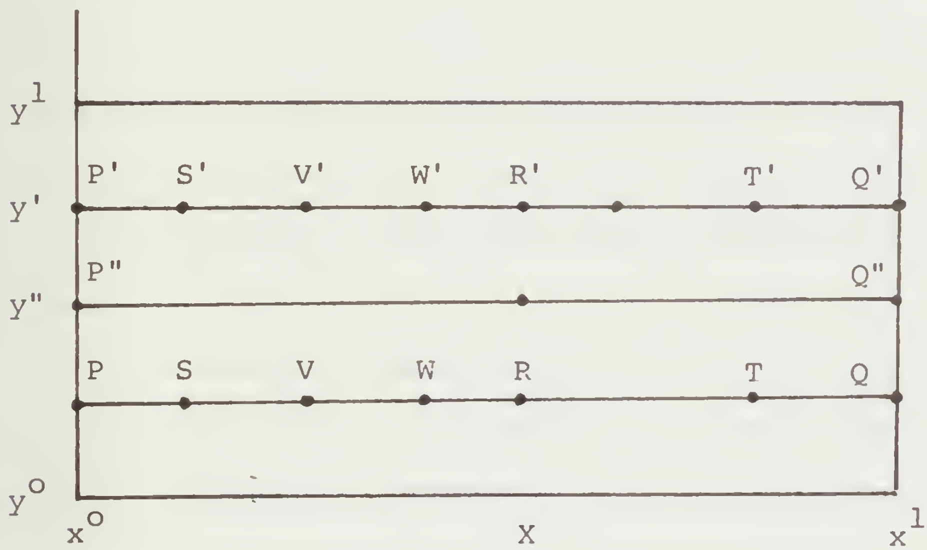
$$L_3 \equiv \begin{cases} \xrightarrow{1/2} & x_1, y_1 \\ \xrightarrow{1/2} & x_2, y_2 \end{cases} \qquad L_4 \equiv \begin{cases} \xrightarrow{1/2} & (x_1, y_2) \\ \xrightarrow{1/2} & (x_2, y_1) \end{cases}$$

are indifferent, where neither (x_1,y_2) or (x_2,y_1) are indifferent to (x_1,y_1). On the other hand if there exists any L_3 and L_4 such that they are not indifferent, then clearly additive independence cannot hold. The beauty of additive independence is that the two attribute utility function (x,y) is merely described over the consequence space by the addition of the separate conditional utility functions x and y. Unfortunately, however very few problems in decision analysis and utility assessment turn out to be additive independent.

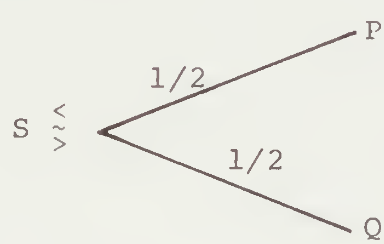
III. <u>Utility Independence</u>

With the same scalar attributes x and y being assessed over the consequence space $x^o \leq x \leq x'$ and $y^o \leq y \leq y'$, utility independence is verified by the

following means. First of all a new consequence space is constructed to include consequences P, Q, R, S, etc.



To verify whether x is utility independent of y the decision maker is asked whether he prefers < P, Q >, a lottery yielding either P or Q with equal probability, or S.

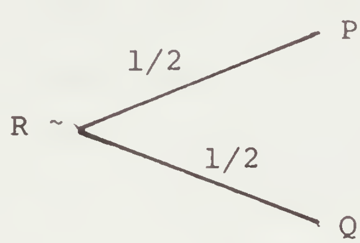


The consequence S is chosen so that a particular answer is expected. The expected answer being that he would prefer the lottery. The decision maker is then asked

whether he prefers < P, Q > or T where again T is chosen as that the expected choice would be the lottery once again. Next the D/M is inquired about the preferences of < P, Q > relative to w. Since w is close to S one might expect the lottery to be preferred once again however not necessarily. The procedure is continued until a consequence is converged upon such that the lottery < P, Q > and the same consequence say R are equally desirable to the D/M.

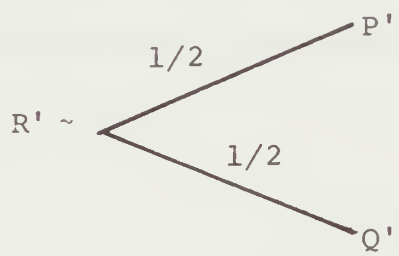
If the decision maker indicates any preferences which do not appear to be consistent with his "true" preferences, it should be pointed out and discussed again.

It should be pointed out that the method of convergence above was done with a fixed value of Y; that is the consequences P, Q, R, S, T and w all had a common amount of z and only differed in their amount of X. Thus R is a certainty equivalent for the lottery < P, Q >.



Next a similar set of questions are asked the D/M but with a different amount of Y say y'. The D/M is asked whether or not he prefers T' to < P', Q' >. To avoid

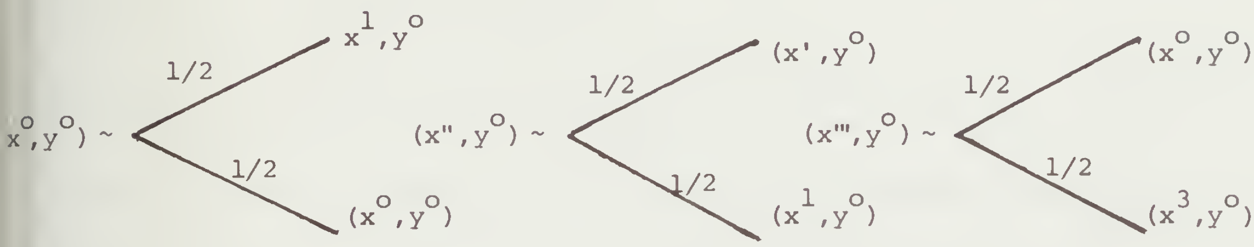
a repetition of the previous answers without thinking about the current questions, T' should be chosen such that the amount of X and not only the amount of Y, in T and T' are different. If the D/M prefers T' to < P', Q' > then his preference is asked about < P', Q' > and S', between < P', Q' > and w' and eventually converge on a consequence R' such that the D/M is indifferent to that and the lottery < P', Q' >



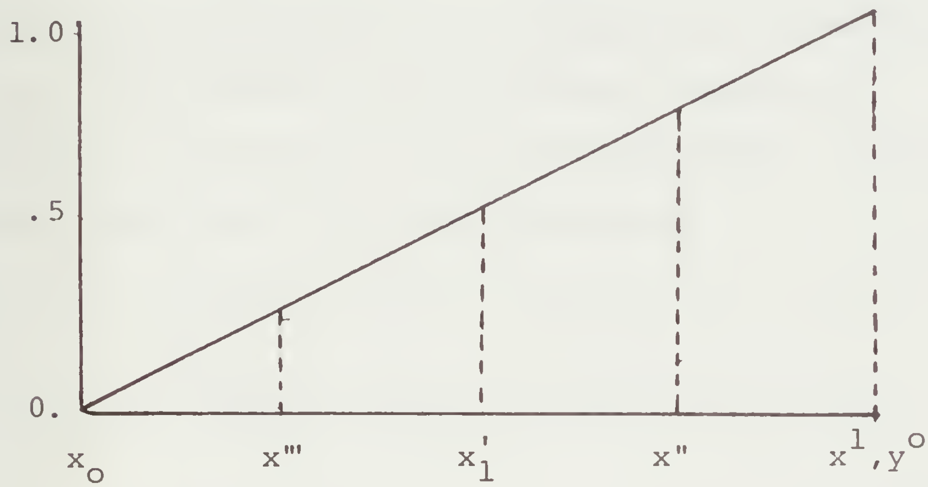
Now if R' and R have the same value of X that is they fall vertically aligned than it appears initially that X is utility independent of Y. This establishes P, Q, R and P', Q', R' have the same relative preference.

As a final check a new amount of Y is chosen - y" and the procedure is repeated with the lottery < P", Q" >. If the D/M converges upon R" as being indifferent to the lottery then utility independence of X to Y is reasonably assured. However, an additional check could be to test the D/M's indifference to a lottery < P", R" > and < P, R > and check to see if the certainly equivalent has the same amount of X.

a vector then the conditional utilities are assessed in the same manner as a single attribute untility function.



If the utility of (x^1, y^o) is arbitrarily set at 1 and the utility of (x^o, y^o) is arbitrarily set at 0 then the complete curve can be constructed with the above information.



From the three loteries above it's obvious that $u(x', y^o) = 5$ $u(x'', y^o) = .75$ and $u(x''', y^o) = .25$.

<u>Assessing the Scaling Constants</u>

The form of the utility function $u(x,y)$ is specified in terms of a number of conditional utility functions over

either X or Y and scaling constants. If there are N and M conditional utility functions for X and Y respectively and there are R scaling constants,

$$u(x,y) = f[u'_X(x), \ldots u_X^N(x),\ u'_Y(y), \ldots u_r^m)y),\ k_1,\ k_2 \ldots k_R], \tag{1}$$

where f is specified and all the utility functions can be scaled from zero to one since the scaling constants are used to insure internal consistency.

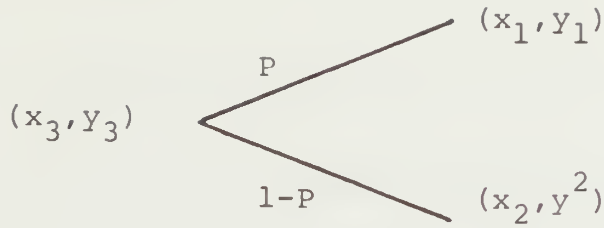
The k's are evaluated by obtaining an evaluating R independent equations with R unknowns, which are generated from certainty considerations, probabilistic considerations or both. For instance using certainty scaling, if consequences (x,y) and x_2,y_2) are indifferent, then by equating utilities in the above equation.

$$f[uX'(x_1), \ldots u_X^N(x_1),\ u'_Y(y_1), \ldots u_Y^m(y_1), k, \ldots, k_R] =$$

$$f[u'_X(x_2), \ldots u_X^N(x_2),\ u'_Y(y_2), \ldots u_Y^m(y_2),\ k, \ldots k\ 12]$$

One equation exists with at most R unknowns. The u_X^m's and u_Y^m's are known since they have already been assessed.

If probabilistic scaling is used then a consequence must be chosen so that it is indifferent to a lottery with probability p of occurring.



By equating expected utilities:

$$u(x_3,y_3) = pu(x_1,y_1) + (1-p)u(y_2,y_2)$$

and combining with equation (1) an equation is obtained involving $k_1, \ldots k_R$ as the only unknowns.

Therefore by using either certainty scaling or probabilistic scaling R independent equations are generated with the R k_R's as the only unkowns. For example the quasi-additive utility function:

$$u(x,y) = k_X u_X(x) + k_Y u_Y(y) + k_{YX} u_X(x) u_Y(y) \tag{2}$$

has origins for u, u_X, y_X:

$$u(x^o, y^o) = 0, \; u_X(x^o) = 0, \; u_Y(y^o) = 0$$

and a consequence space:

$$x^o \leq x \leq x' \quad \text{and} \quad y^o \leq y \leq y'$$

which yields:

$$u(x,y) = f[u_X(x),\ y_Y(y),\ k_X,\ k_Y\ k_{XY}]$$

where k_X, k_Y, k_{XY} are the unknown scaling contants.

If it is assumed that both x and y are increasing in preference then the utility functions are scaled by

$$u(x',y') = 1,\ u_X(x') = 1,\ u_Y(y') = 1$$

Using these utilities and equation (2) evaluated at (x', y') then one finds:

$$1 = k_X + k_Y + k_{XY}. \qquad (3)$$

Evaluating (2) at (x',y^o) and (x^o, y') respectively yields the following:

$$u(x', y^o) = k_Y \quad \text{and} \quad u(x^o, y') = k_Y. \qquad (4)$$

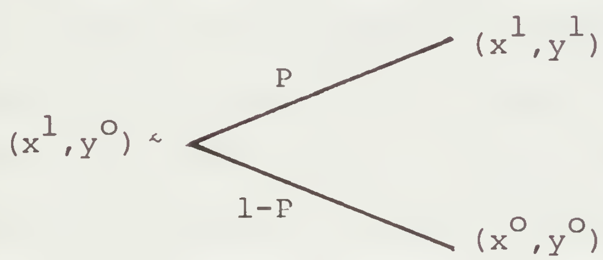
The decision maker must then be asked if he prefers (x', y^o) or (x^o, y'). If the former is preferred then from (4) $k_X > k_Y$ and if the latter is preferred then $k_Y > k_X$ and if they are indifferent then $k_X = k_Y$. If $k_X > k_Y$ then a consequence may be found such that (x', y^o) and (x^o, y') are indifferent and their utilities may be equated using (2).

$$k_Y = k_X\ u_X(x') \qquad (5)$$

where $u_X(x')$ is known.

To help the decision maker identify y', one might present him with a specific choice between (x, y^o) and (x^o, y') with x fixed. If the first consequence were preferred to the second, x would be decreased and the binary choice reoffered and vica-versa. With this approach one should converge on x'.

If probabilistic scaling is used then a probability p must be obtained such that the decision maker is indifferent between a consequency (x', y^o) and the lottery. $[(x',y'); p_X; (x^o,y^o)]$.



By using (2) again it follows that $k_X = p_X$ and together with (3), (5) the quantities k_X, k_Y and k_{XY} can be solved.

<u>Consistency Check</u>

Once the utility function of $u(x,y)$ has been formulated then a consistency check should be performed to detect errors in the decision maker's utility function

and determine whether the function represents his true preferences. This can be accomplished by several methods which include paired comparisons of various consequences. With the utility function $u(x,y)$ the D/M is asked whether he prefers (x_a,y_a) to (x_b,y_b). If (x_a,y_a) is preferred then it naturally must have a higher utility value than (x_b,y_b) to be consistent. Obviously this check can be performed repeatedly, however, it is recommended that the D/M is posed with easier comparisons to start off.

A second method involves the emprical determination of whether or not the D/M is risk averse in positive rays of the form (x, cx) where $c > 0$. The D/M is asked what consequence (x_1,cx_1) is indifferent to (cx_2,cx_2); 1/2; $(x_3,cx_3))$ where (x_2,cx_1) is if x_1 is less than $(x_2 + x_3)/2$ then the D/M is ray risk averse. For ray risk aversion for preferences increasing in X and Y $u'(x,cx)$ must be positive and $u''(x,cx)$ must be negative for all x, where u' and u'' devote first and second derivatives with respect to X.

APPENDIX B

This section describes the results of the decision analyses methodology for a "Design to Performance" or a "Design to Change" type philosophy. The same approach as Chapter 5 for the Design to Cost philosophy was followed in this section. However, the results were as expected somewhat different because the D/M was more interested in availability rather then cost and was more willing to trade off the acquisition cost for the increased availability. In so doing, however, the D/M showed a risk aversion to a ship with low availability.

A. Utility Function Development

1. Consequence space:

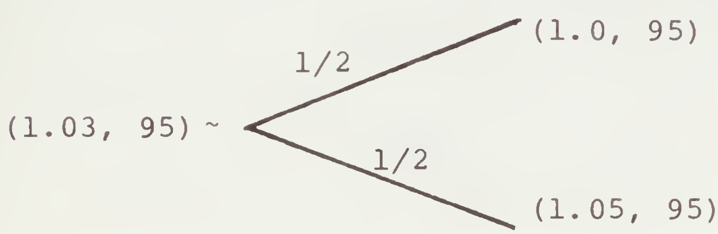
    1.0×10^8 x 1.05×10^8 - acquisition cost

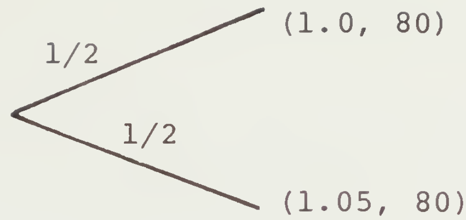
    75% y 95% - availability

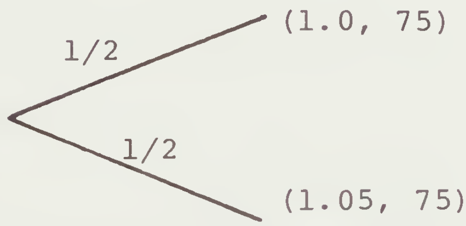
2. Utility Independence

    Utility independence was again verified from the following lottery results:

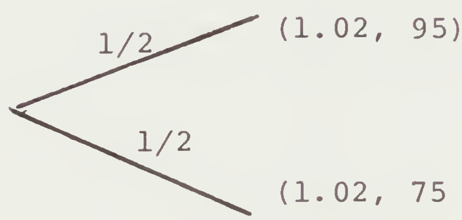
2a.

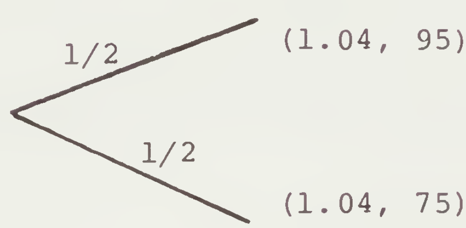


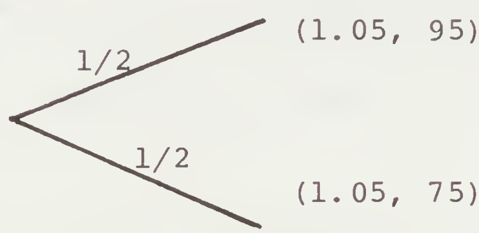
(1.03, 80) ~ 

(1.03, 75) ~ 

2b.

(1.02, 83) ~ 

(1.04, 83) ~ 

(1.05, 83) ~ 

∴ x and y are utility independent Fig. 37 & 38.

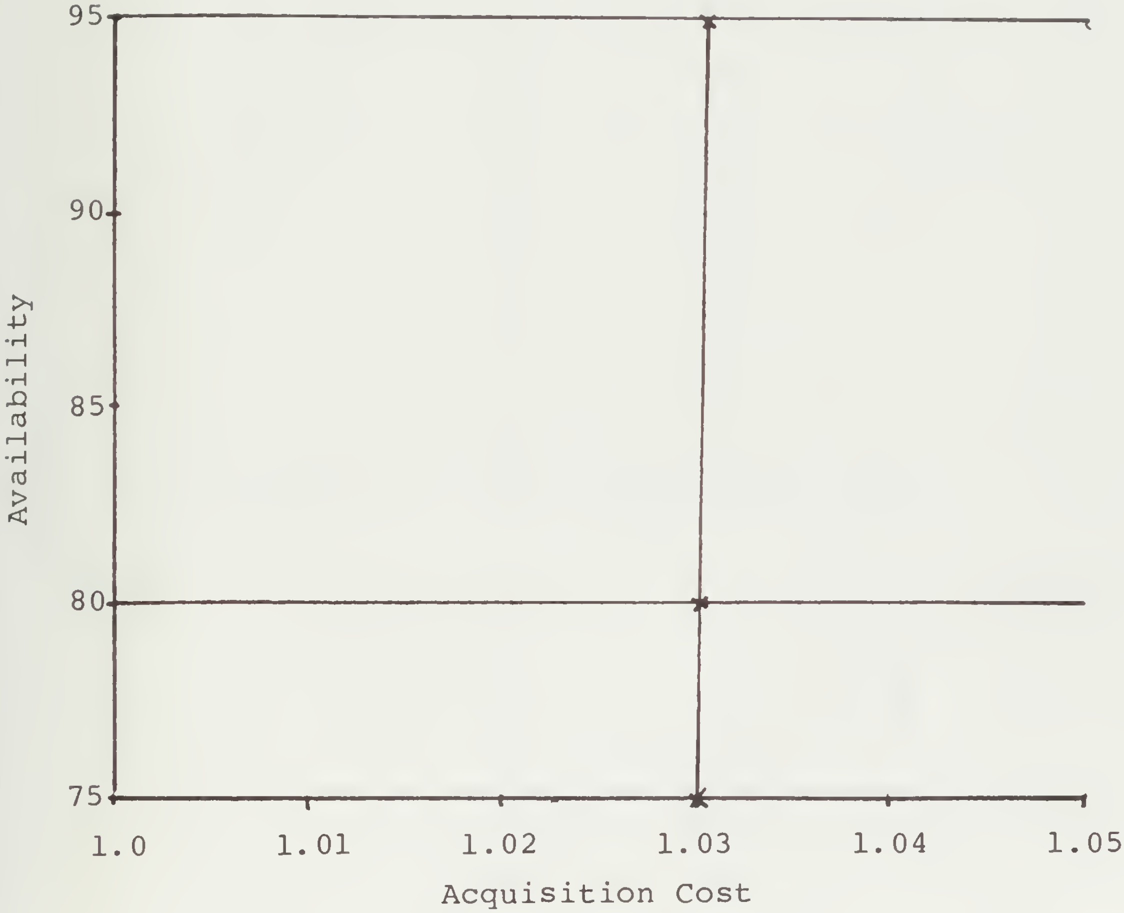


FIGURE 37 Utility Independence X of Y

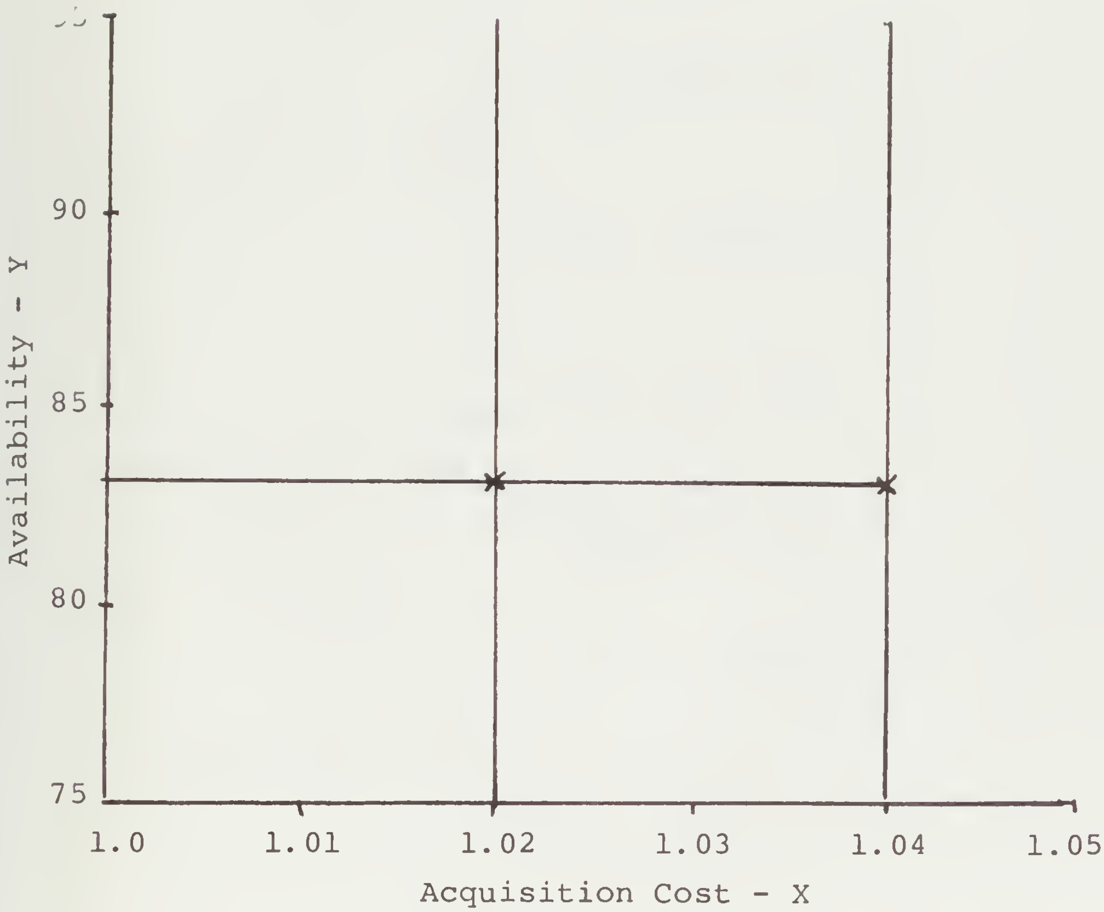


FIGURE 38 Utility Independence Y of X

3. <u>Conditional Utility Functions</u>

a. The following scale was arbitrarily set:

$$u_1(1.0,\ 95) = 0.0$$

$$u_1(1.05,\ 95) = -\ 1.0$$

$$u_2(1.0,\ 95) = 0.0$$

$$u_2(1.0,\ 75) = -\ 1.0$$

b. The results of the following lotteries described the u_1 function

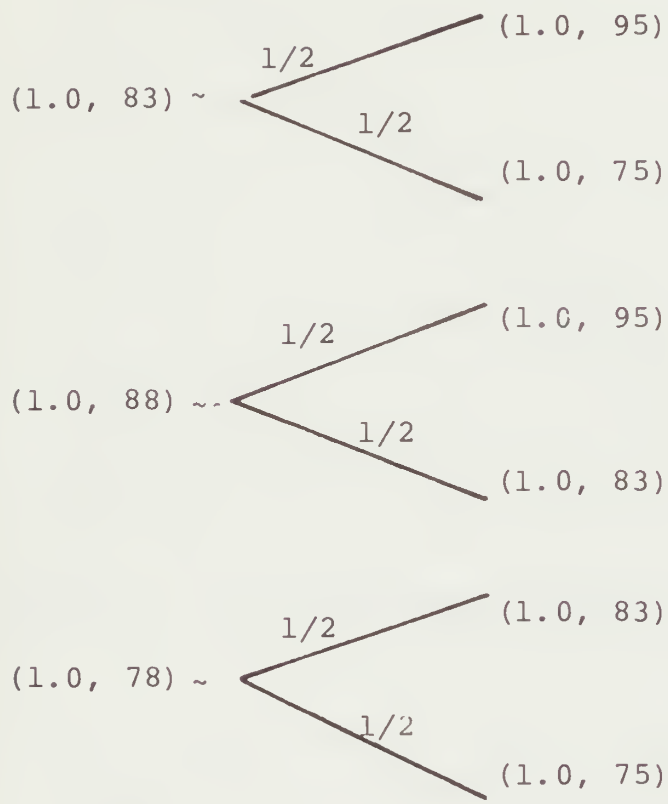
$$(1.03,\ 95) \sim \begin{array}{ll} \xrightarrow{1/2} & (1.0,\ 95) \\ \xrightarrow{1/2} & (1.05,\ 95) \end{array}$$

$$(1.015,\ 95) \sim \begin{array}{ll} \xrightarrow{1/2} & (1.0,\ 95) \\ \xrightarrow{1/2} & (1.03,\ 95) \end{array}$$

$$(1.04,\ 95) \sim \begin{array}{ll} \xrightarrow{1/2} & 1.03,\ 95 \\ \xrightarrow{1/2} & (1.05,\ 95) \end{array}$$

The condition utility function for $u_1(x,95)$ is plotted in Figure 39.

c. The results of the following lotteries described the u_2 function.



The condition utility function for u_2 (1.0,y) is plotted in Figure 40.

4. Computing the Scaling Constants

a. The following scale was arbitrarily set:

$$u(1.0,\ 95) = 0.0$$

$$u(1.05,\ 75) = -\ 1$$

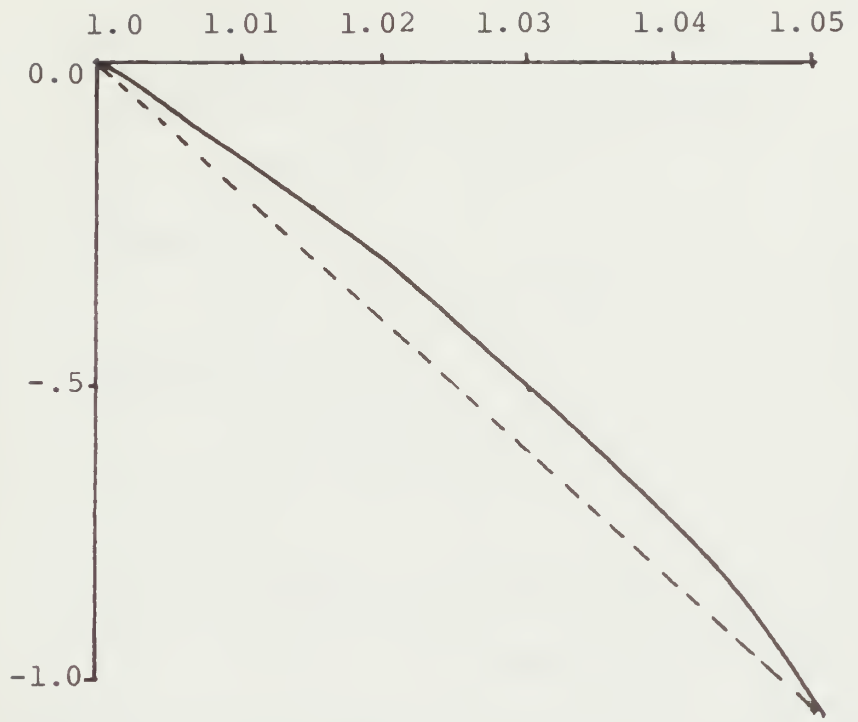


FIGURE 39 Conditional Utility Plot $u_1(x, 95)$

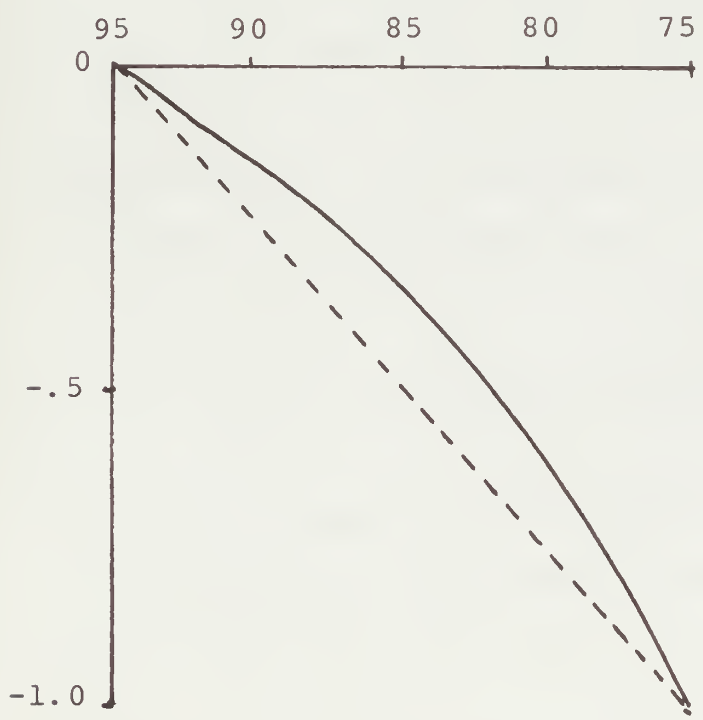


FIGURE 40 Conditional Utility Plot $u_2(1.0,y)$

b. In addition the D/M was indifferent between the following consequences:

$$(1.05,\ 95) \sim (1.0,\ 85)$$

however:

$$(1.05,\ 95) > (1.0,\ 75)$$

c. Define a_1 and a_2:

$$u(1.05,\ 95) = a_1$$

$$u(1.0,\ 75) = a_2$$

$$u(x,95) = -\ a_1u_1(x,\ 95)$$

$$u(1.0,y) = -\ a_2u_2(1.0,y)$$

d. By substitution:

$$-a_1u_1(1.05,95) \sim -a_2u_2(1.0,\ 85)$$

however from Figure 40, $u_2(1.0,85) = .4$

$\therefore\ a_1 = -\ a_2(-.4)$

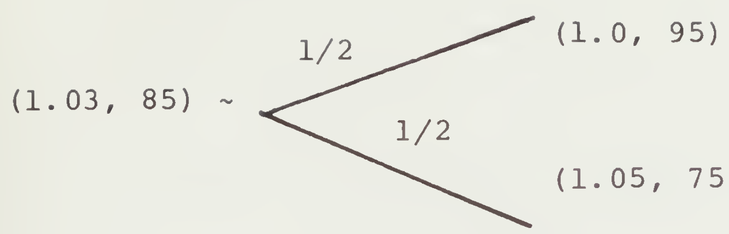
$a_1 = .4a_2$

e. The basic utility function as in Chapter 5 took on the following form:

$$u(x,y) = -a_1u_1(x,95)\ -a_2u_2(1.0,y)$$

$$+\ \frac{-1-a_1-a_2}{a_1a_2}\ (-a_1u_1(x,95))(-a_2u_2(1.0,y)$$

f. The D/M chose the consequence (1.03, 85) indifferent to the below lottery:



$$E(u) = 1/2(0) + 1/2(-1)$$

$$= - 1/2$$

$$\therefore\ u(1.03, 85) = - 1/2$$

g. $u(1.03,85) = - 1/2 = - .4a_2u_1(1.03,95)$

$$- a_2u_2(1.0, 85)$$

$$+ \frac{-1-1.4a_2}{.4a_2^2}(-.4a_2u_1(1.03,95))(-a_2u_2(1.0,85)$$

from Figures 39 and 40.

$$u_1(1.03,95) = - .5$$

$$u_2(1.0, 85) = - .4$$

substituting these utilities into the above relation:

$$a_2 = - .9375$$

$$a_1 = - .375$$

h. The utility function of $u(x,y)$ turned out to be:

$$u(x,y)=.375u_1(x,95)+.938u_2(1.0,y)$$

$$+ .312u_1(x,95)u_2(1.0,y)$$

In order to shift eh scale so that $u(1.0,95) = 1.0$ and $u(1.05,75) = 0.0$ 1.0 was added to the utility function.

$$u(x,y)=.375u_1(x,95) + .938u_2(1.0,y) + .312u_1(x,95)u_2(1.0,y) + 1.0$$

The 3-dimensional plane that describes $u(x,y)$ is plotted in Figure 41.

B. Decision Tree Development

For the normal form of decision tree analysis it was again assumed that in addition to the high and low level modular designs, two intermediate levels of design existed. The acquisition cost for each level was the same and also the availability was the same for each state of nature as in Chapter 5, (see Table 2 and 3).

The utilities for each level and for each state of nature appear in the table below:

		No. of M & C		
		1	2	3
	High	.625	.5	.469
Modular	A	.702	.52	.41
Level	B	.688	.47	.303
	Low	.625	.44	.062

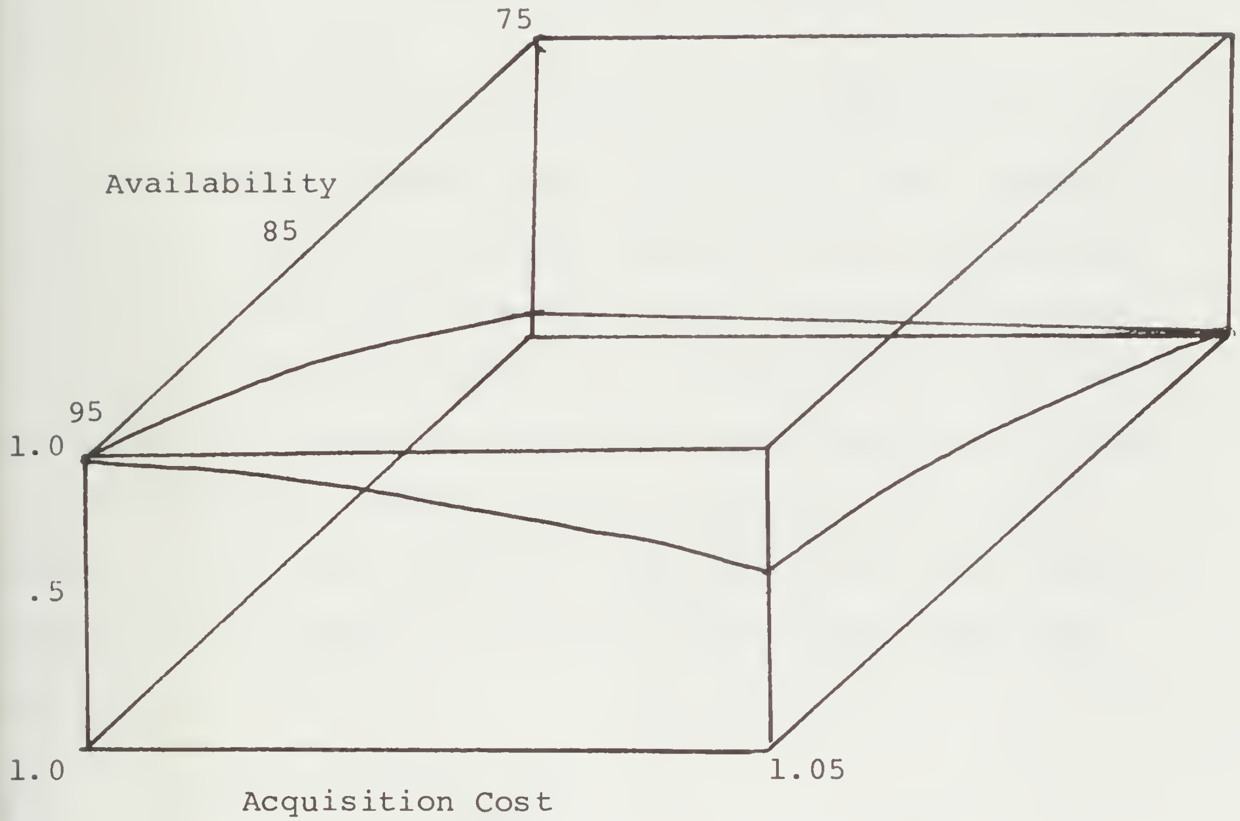


FIGURE 41 Utility Plane for Design to Performance

NOTE: All utilities have been scaled up by 1.0 in order to place the plane in the positive sector.

The above utilities were substituted into the exact same tree with the same probabilities for the states of nature, outcomes, and the conditional probabilities as in Chapter 5 (Figure 42). It was assumed that little reason existed to change the probabilities at the various chance nodes because the philosophy of the design should in no way have influenced them.

The results of the decision tree should once again that the optimal strategy was to follow the lower branch and gather additional information. However, this assumed that this process was cost free to the D/M. Because the optimal strategy in the upper branch (e.g. design level B) was only .01 utilities less than that of the lower branch then if an acquisition cost increase had been imposed on the modular design in the lower branch to cover the cost of the study, the strategy to design and build level B would have been optimal.

C. Sensitivity Analysis

Again in order to simplify the probability sensitivity analysis the problem was condensed to a two state of nature, two outcome two act problem. Also the probabilities for the above items remained the same. An acquisition cost increase of $250,000 was imposed on the lower level design candidates to cover the cost of the study.

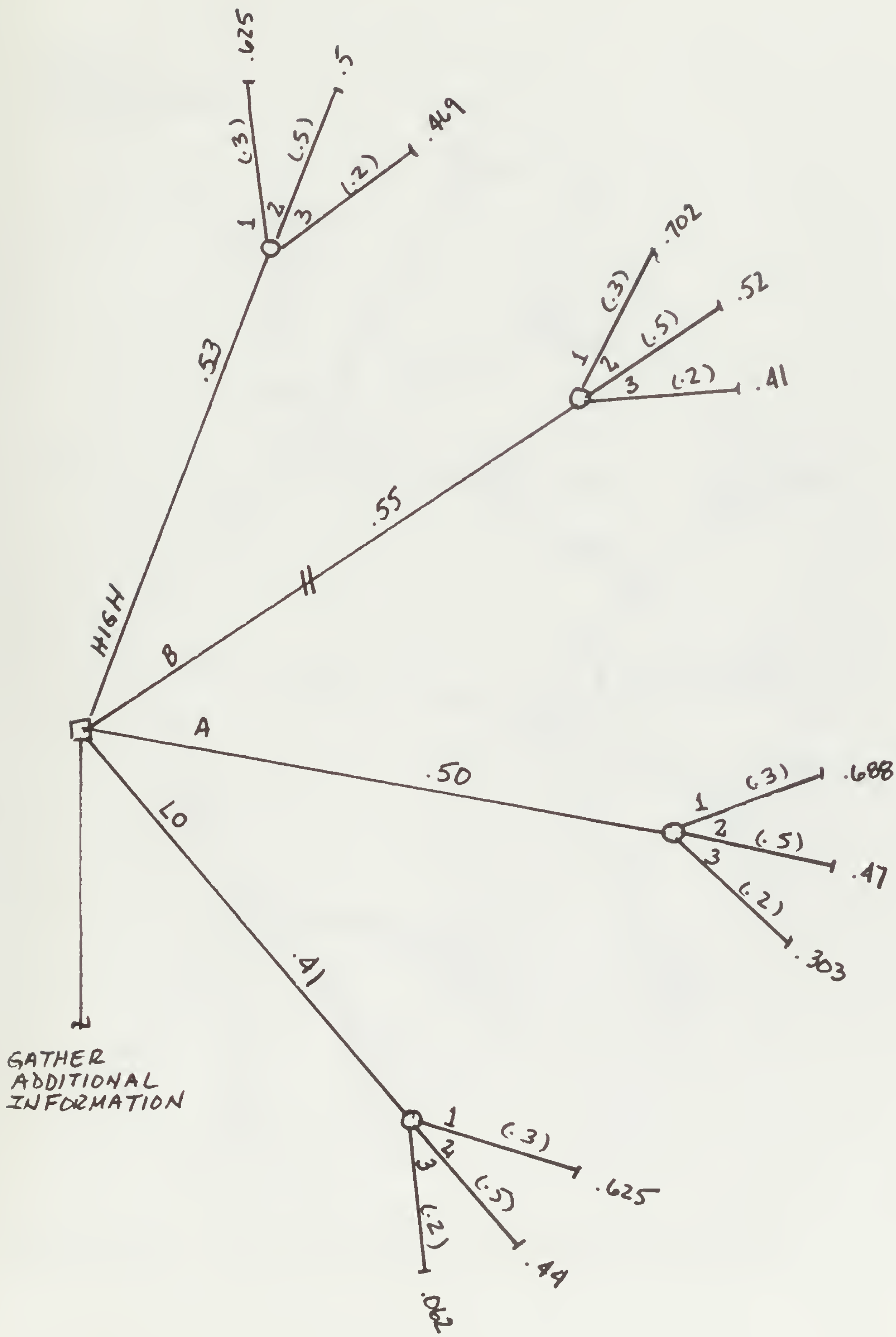


FIGURE 42a Upper Decision Tree Branch for "DTP"

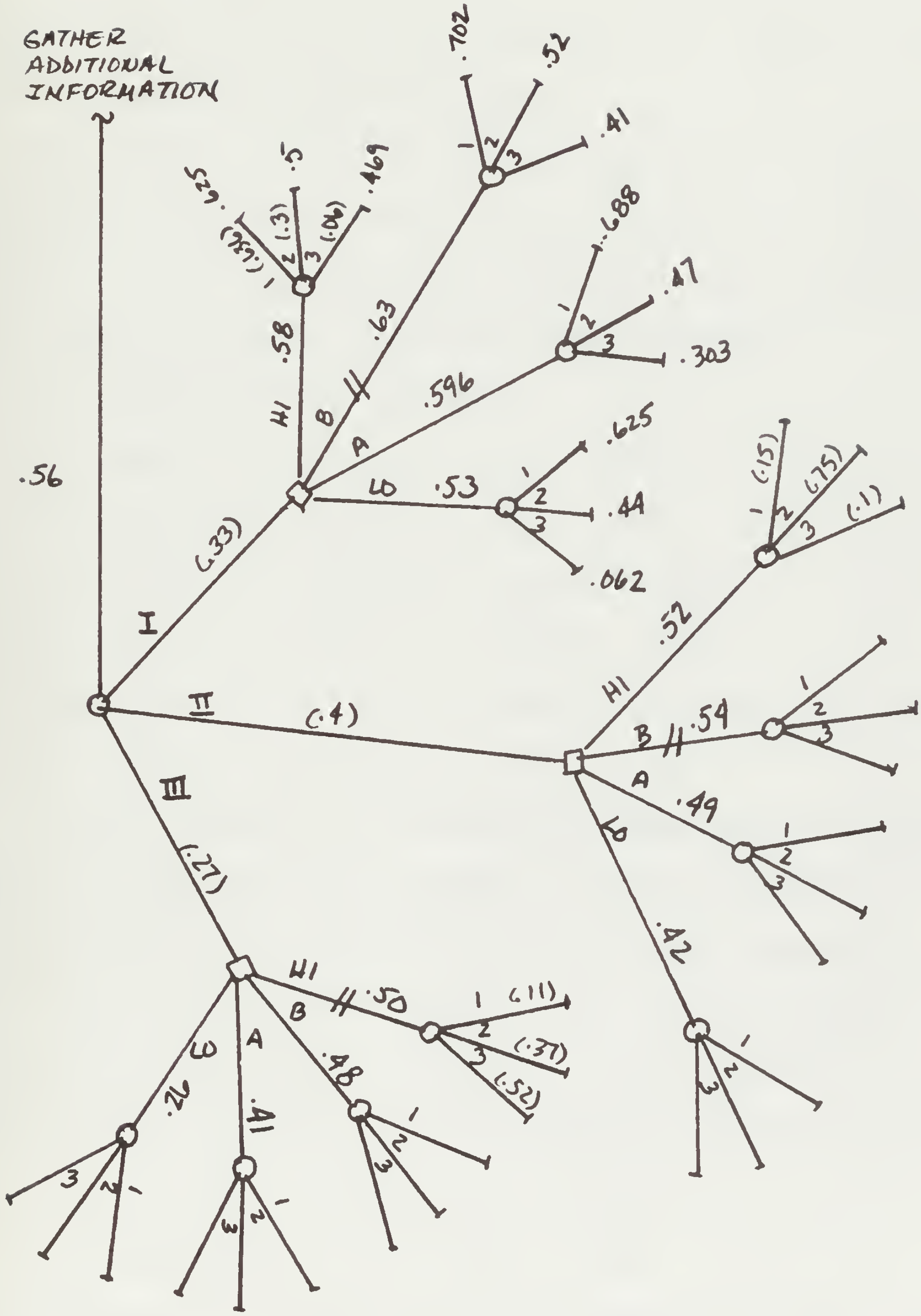


FIGURE 42b Lower Decision Tree Branch for "DTP"

From Figure 42 by averaging out and folding back it was obvious that the optimal strategy was not to engage in a study but to build the modular design.

An extensive form of analysis (Table 6) was next conducted utilizing the decision tree in Figure 43. Again from column 3 and 4 the equations describing each strategy over the range of probabilities of a ship requiring 1 M & C per lifetime were formulated.

1. $.625(P) + .43(1-P) = .43 + .195\ P$

2. $.625(P) + .5(1-P) = .15 + .125\ P$

3. $.612\ P + .444(1-P) = .444 + .168\ P$

4. $.614\ P + .465\ (1-P) = .465 + .149\ P$

5. $.615\ P + .429\ (1-P) + .429 + .186\ P$

6. $.610\ P + .48\ (1-P) = .48 + .13\ P$

Like the sensitivity analysis performed for the DTC philosophy in Chapter 5 one strategy remained optimal throughout the entire range of P; that strategy being to build the high level modular design. However, one point worth mentioning and that is that at P = 1.0 strategy 1 (to build low level design) is also optimal, (Figure 44).

$$u(\text{strategy } 2 \text{ @ } P = 1.0) = .625$$

$$u(\text{strategy } 1 \text{ @ } P = 1.0) = .625$$

Although it appears unlikely that this probability will occur the point is still worth mentioning.

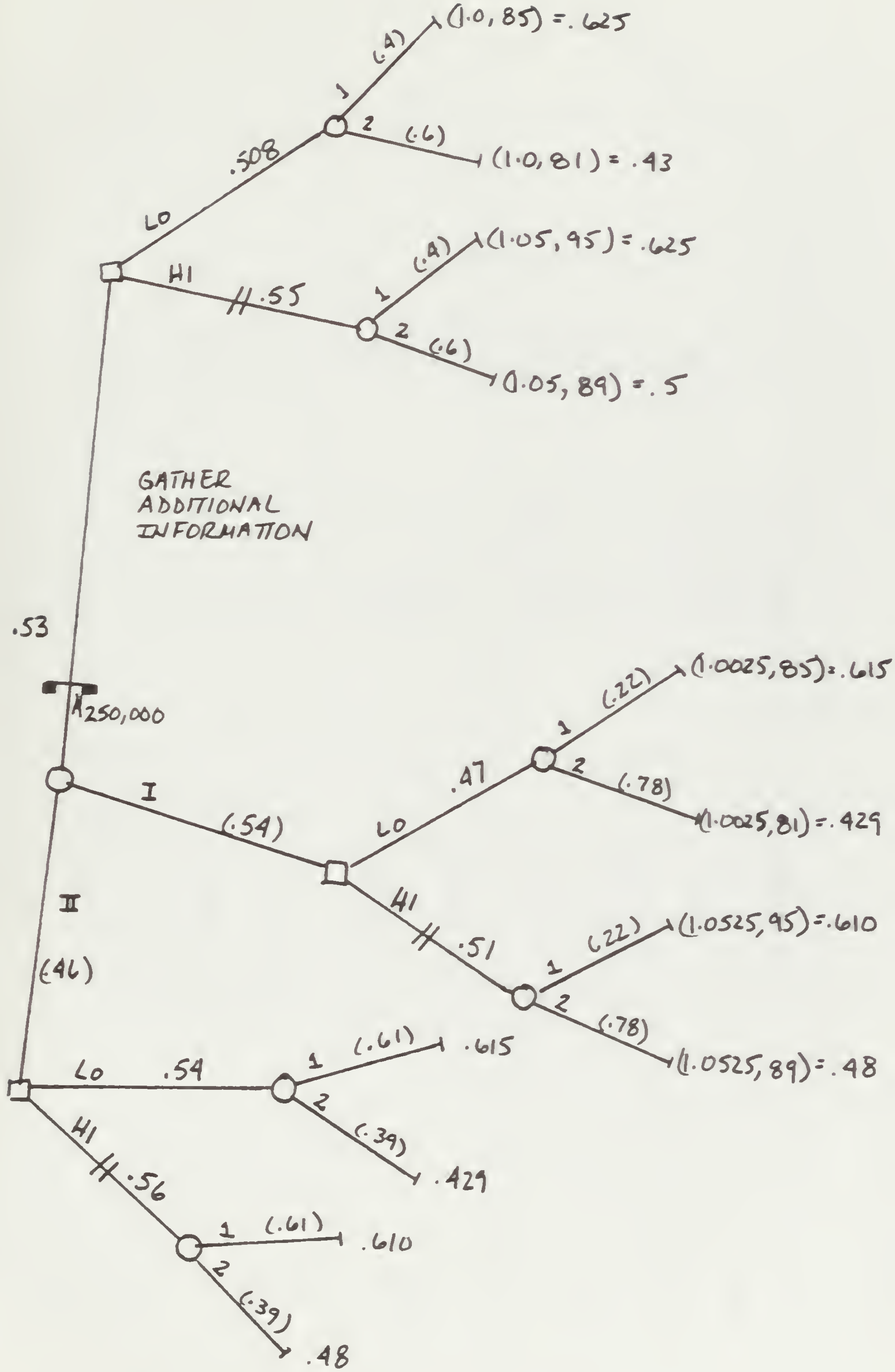


FIGURE 43 Extensive Analysis Decision Tree

TABLE 6 Extensive Analysis Under DTP With Test Cost

Strategy	Decision	1 (.4)	2 (.4)	ENV
Build Baseline		.625	.43	.508
Build Modular*		.625	.5	.55
	If I Build High	.615 (.3)	.429 (.7)	
Test		.612	.444	.51
	If II Build Low	.610 (.7)	.48 (.3)	
	If I Build	.610 (.3)	.48 (.7)	
Test		.614	.465	.525
	If II Build	.615 (.7)	.429 (.3)	
	If I Build	.615 (.3)	.429 (.7)	
Test		.615	.429	.50
	If II Build	.615 (.7)	.429 (.3)	
	If I Build	.610 (.3)	.48 (.7)	
Test		.610	.48	.53
	If II Build	.610 (.7)	.48 (.3)	

*Optimal Strategy

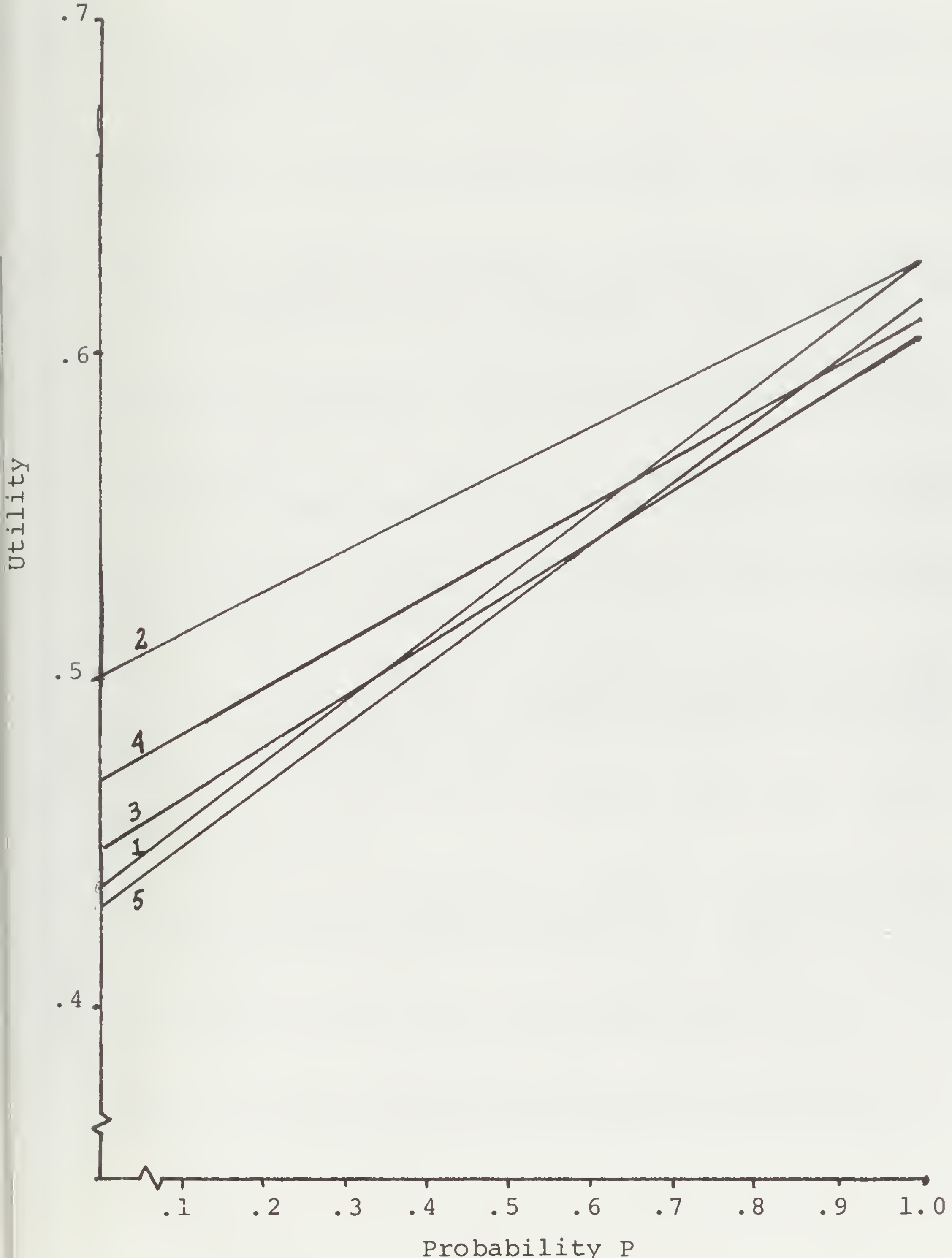


FIGURE 44 Strategy Plot

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Thesis
C747525 Cook 165479
The impact of modular ship design of the life cycle of a naval vessel.